TEMPERATURE/EMISSIVITY SEPARATION FOR HYPERSPECTRAL DATA

Christoph C. Borel, PhD

AFRL Distinguished National Lab Fellow

Space Vehicles Directorate

Air Force Research Laboratory

And support from AFRL: Drs Michael Hoke, Ronald Lockwood, Gail Anderson and SSI: Marsha Fox

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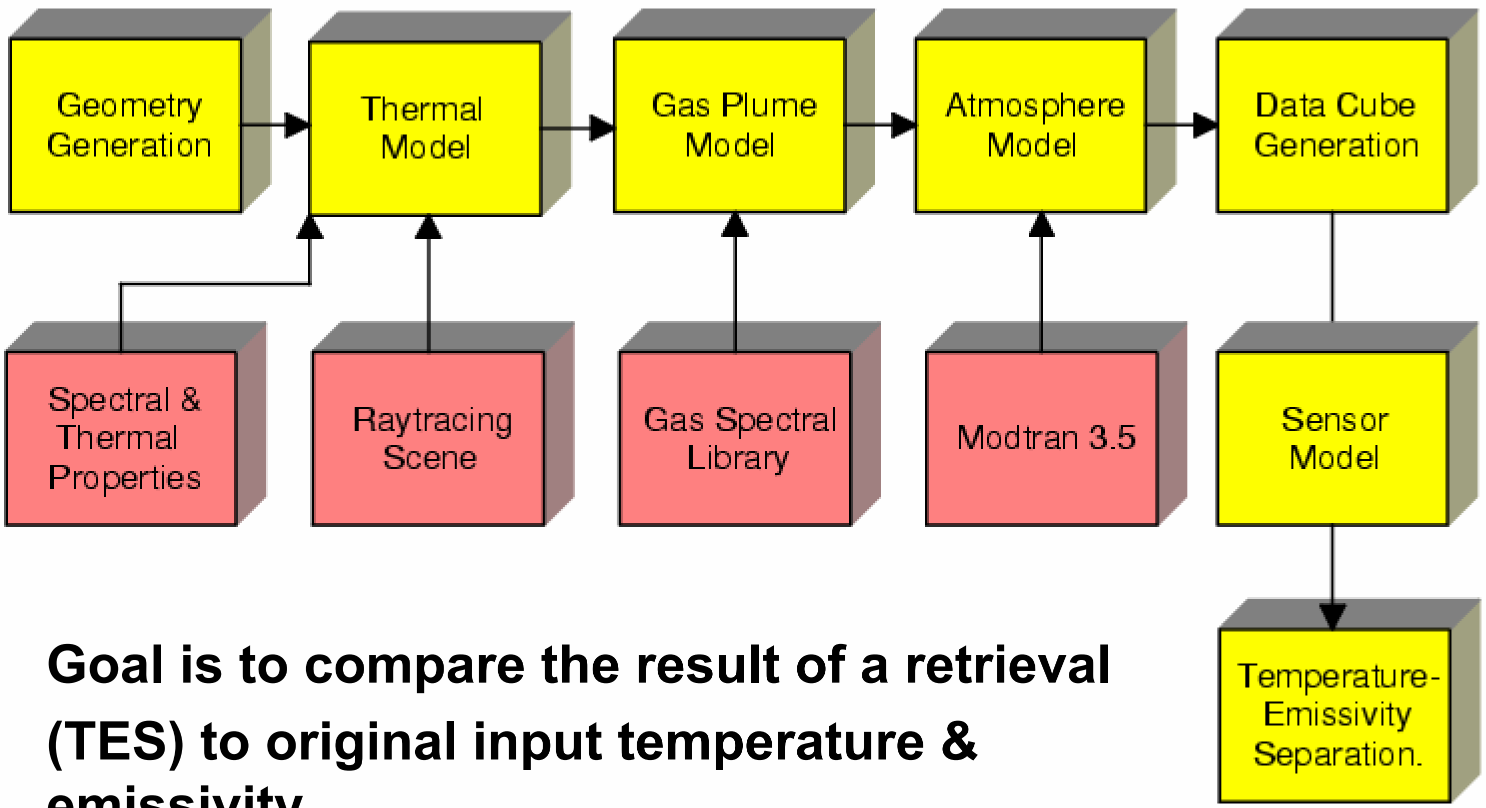
- Hyperspectral scene & sensor modeling
- Why atmospheric correction is necessary
- Temperature-Emissivity Separation (TES)
  - A novel implementation of the In-Scene Atmospheric Correction Method (ISAC)
  - The “smooth emissivity retrieval” combined with ISAC
  - Dimensionality analysis of atmospheric look-up tables using spectral angle clustering
- Conclusions

Why synthetic data?

Why synthetic data?

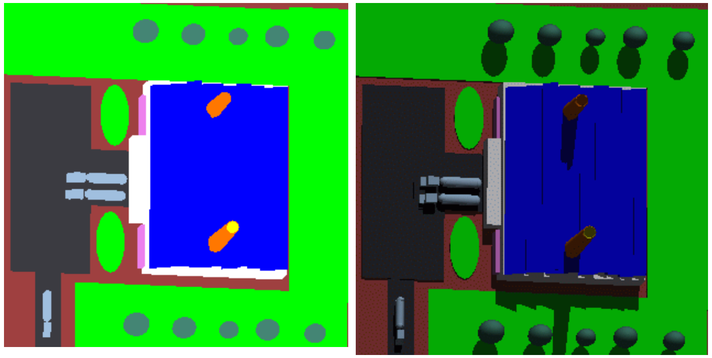
1. Can compare the retrieved emissivity to the truth.
2. Can assume that the sensor's spectral and radiometric performance is optimal.
3. Can perform sensitivity studies by assuming errors in the sensors performance and modeling of the atmosphere which are useful in:
   (a) Determining the retrieval errors for actual sensors
   (b) Come up with sensor specifications (e.g. SNR and spectral resolution) to meet a certain performance goal.

End-to-end modeling

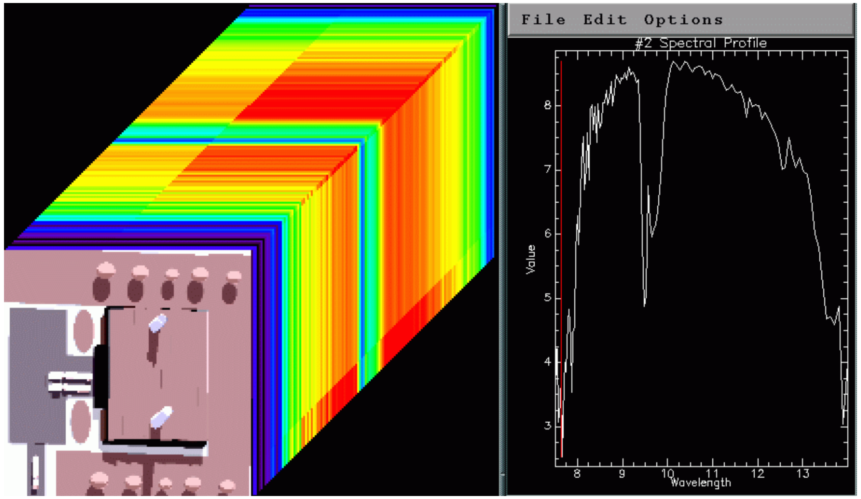


Goal is to compare the result of a retrieval (TES) to original input temperature & emissivity

Hyper-spectral Scene Generation (1)



Raytraced material and shading maps



Simulated Sebass Cube

Problem:

Model ideal input data to test various analysis techniques

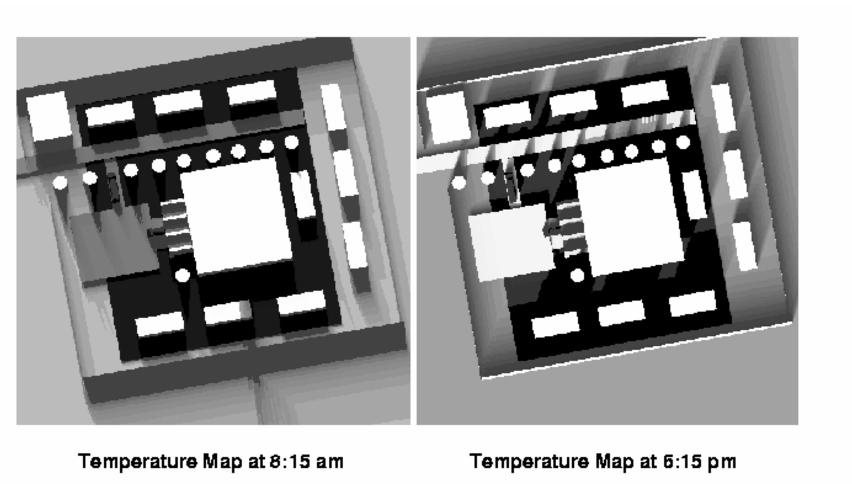
Results:

Generate 1 cm-1 resolution cube at 256x256 pixels in a few minutes.

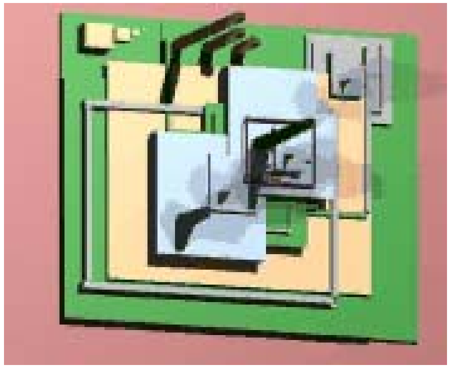
Solution:

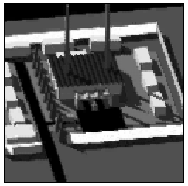
- 3-D CAD model of scene
- Raytrace scene from high-altitude flight path to determine material and shading
- Compute temperature using 1-D finite difference method
- Add 3-D time variable plume
- MODTRAN 3/4 derived atmospheric modeling

Hyper-spectral Scene Generation (2)



Computed temperatures





Simulated over flight   Simulated turbulence

Problems:

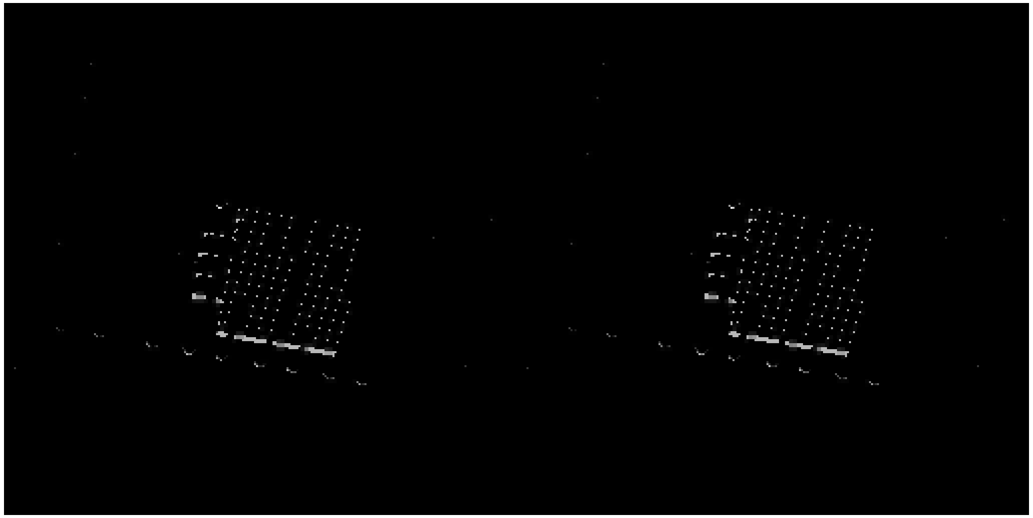
Difficult to model temperature well, only semi-infinite model

Solution:

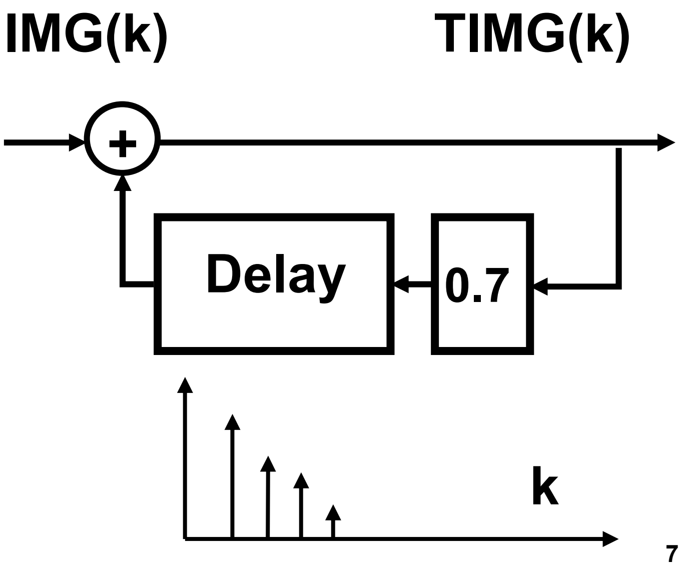
Use a complex combination of public domain software written in C and in-house code written in IDL

Simple thermal model

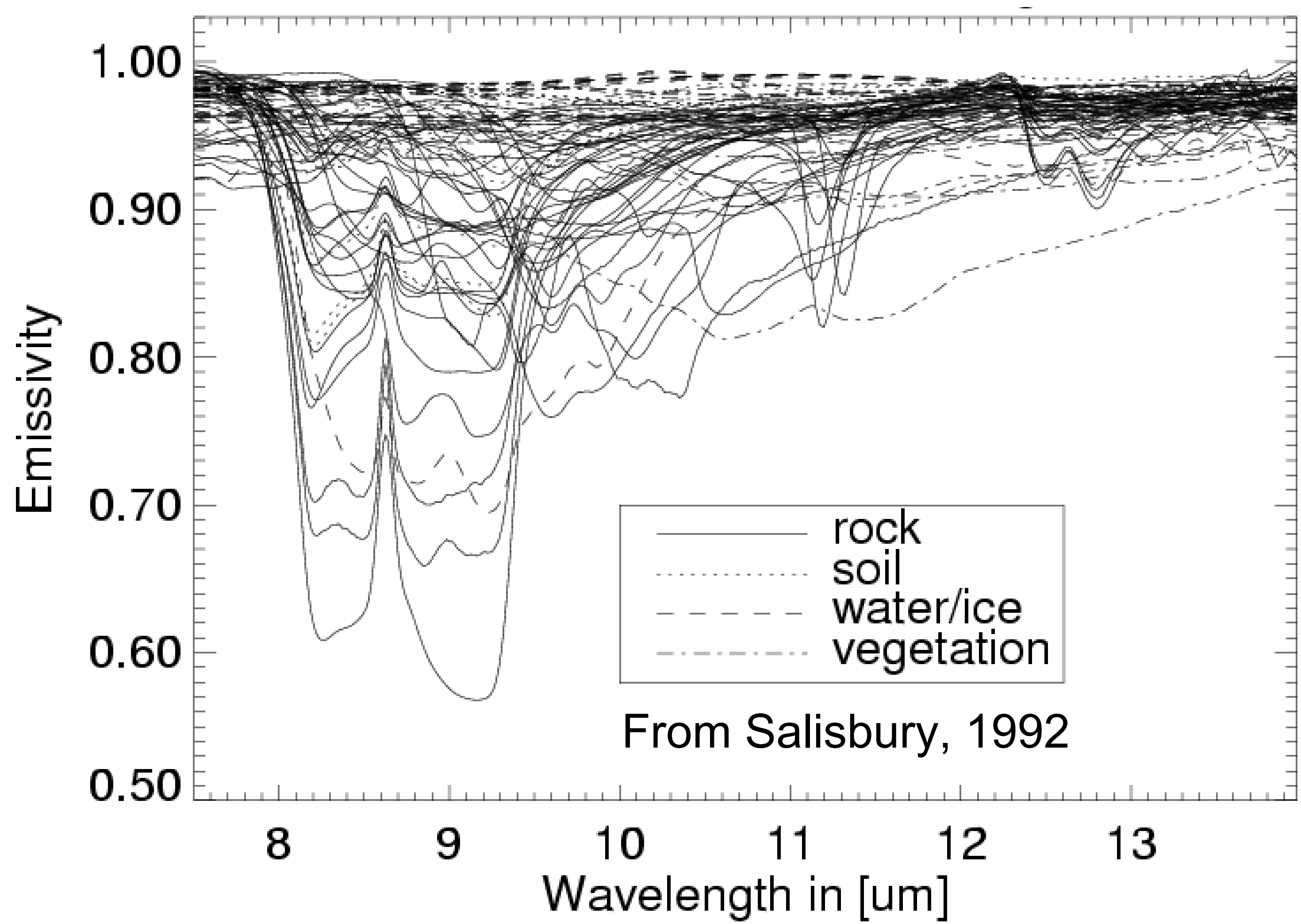
1. A very simple method to simulate heat conduction is delayed image integration: TIMG(k)=IMG(k)+c*TIMG(k-1), where IMG(k) is the current Image
2. Scale the minimum/maximum temperatures to statistics of measured surfaces (e.g. Jacobs "Thermal infrared characterization of targets and backgrounds)



IMG(k) TIMG(k)



Natural surface emissivities



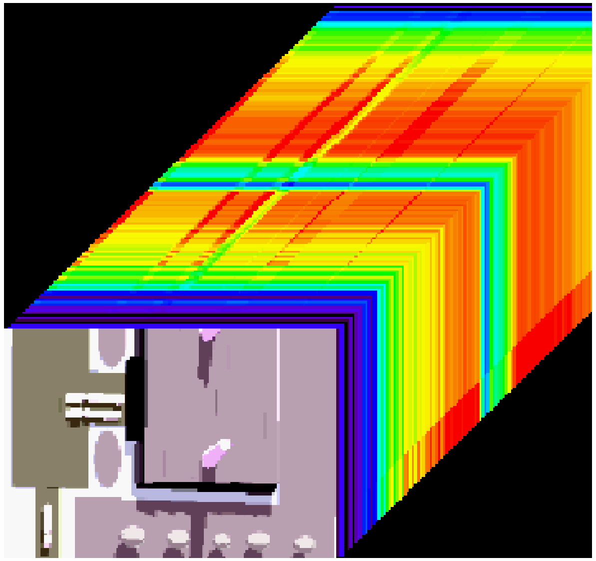
Data cube generation

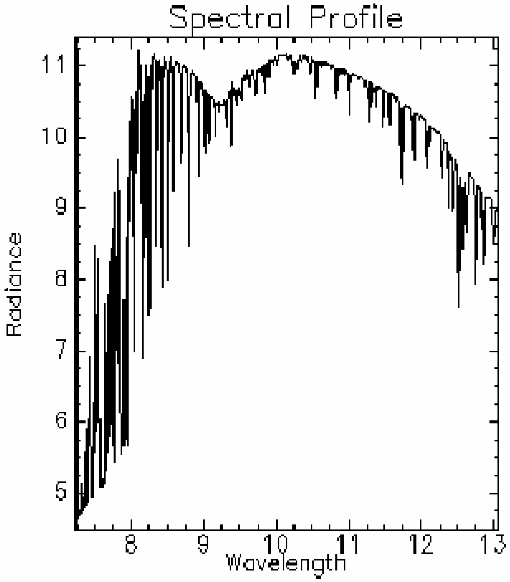
$$L_{total}(x,y,\lambda) = L_{ground}(x,y,\lambda) + L_{gas}(x,y,\lambda) + L_{path\uparrow}(\lambda) + L_{reflected}(x,y,\lambda),$$

where

$$L_{ground}(x,y,\lambda) = \varepsilon(x,y,\lambda)B(\lambda,T_{ground}(x,y))\tau_{gas}(x,y,\lambda)\tau_{atmo}(\lambda),$$
$$L_{gas}(x,y,\lambda) = [1-\tau_{gas}(x,y,\lambda)]B(\lambda,T_{gas})\tau_{atmo}(\lambda),$$
$$L_{reflected}(x,y,\lambda) = L_{path\downarrow}(\lambda)[1-\varepsilon(x,y,\lambda)]\tau_{gas}(x,y,\lambda)\tau_{atmo}(\lambda),$$

and $B(\lambda, T)$ is the Planck function describing the spectral radiance in $[W/(cm^2\ ster\ \mu m)]$.





Simulated thermal hypercube with sample spectrum.

Temperature/Emissivity Separation

Problem of Temperature-Emissivity Separation (TES):

Given are N spectral measurements of radiance and wanted are $N+1$ unknowns (N emissivities and one temperature) [Realmuto, 1990].

If atmosphere present we also need: $3N$ unknowns

- N spectral transmissions $T(\lambda_i)$,
- N up-welling path radiances $L_{path\uparrow(\lambda_i)}$, and
- N down-welling path radiances $L_{path\downarrow}(\lambda_i)$.

Previous Methods: (for multi-spectral case)

- Assumed channel 6 emittance model: Kahle et al., 1980,
- Emissivity Spectrum Normalization (ESN): Realmuto, 1990,
- Thermal log and alpha residual: Hook et al., 1992 and
- Mean-Maximum Difference (MMD): Matsunaga, 1993.

Hyperspectral sensors & an idea…

Hyperspectral Thermal Sensors:

$\Rightarrow$ Potential to separate emissivity, temperature and atmosphere using many channels ($>$ 100) in TIR (8-12 μm).

Simple Observation:

A typical emissivity spectrum is rather smooth compared to spectral features introduced by gases in the atmosphere.

Idea:

Devise an adaptive solution technique to retrieve emissivity spectra ε_i based on spectral smoothness.

Similar approaches by Hook (JPL) using micro-FTIR, Revercomb et al (Uwisc) using AERI and Fox (SSI) in MOSESS

De-correlation wavenumber

Measure of smoothness: Decorrelation wavenumber

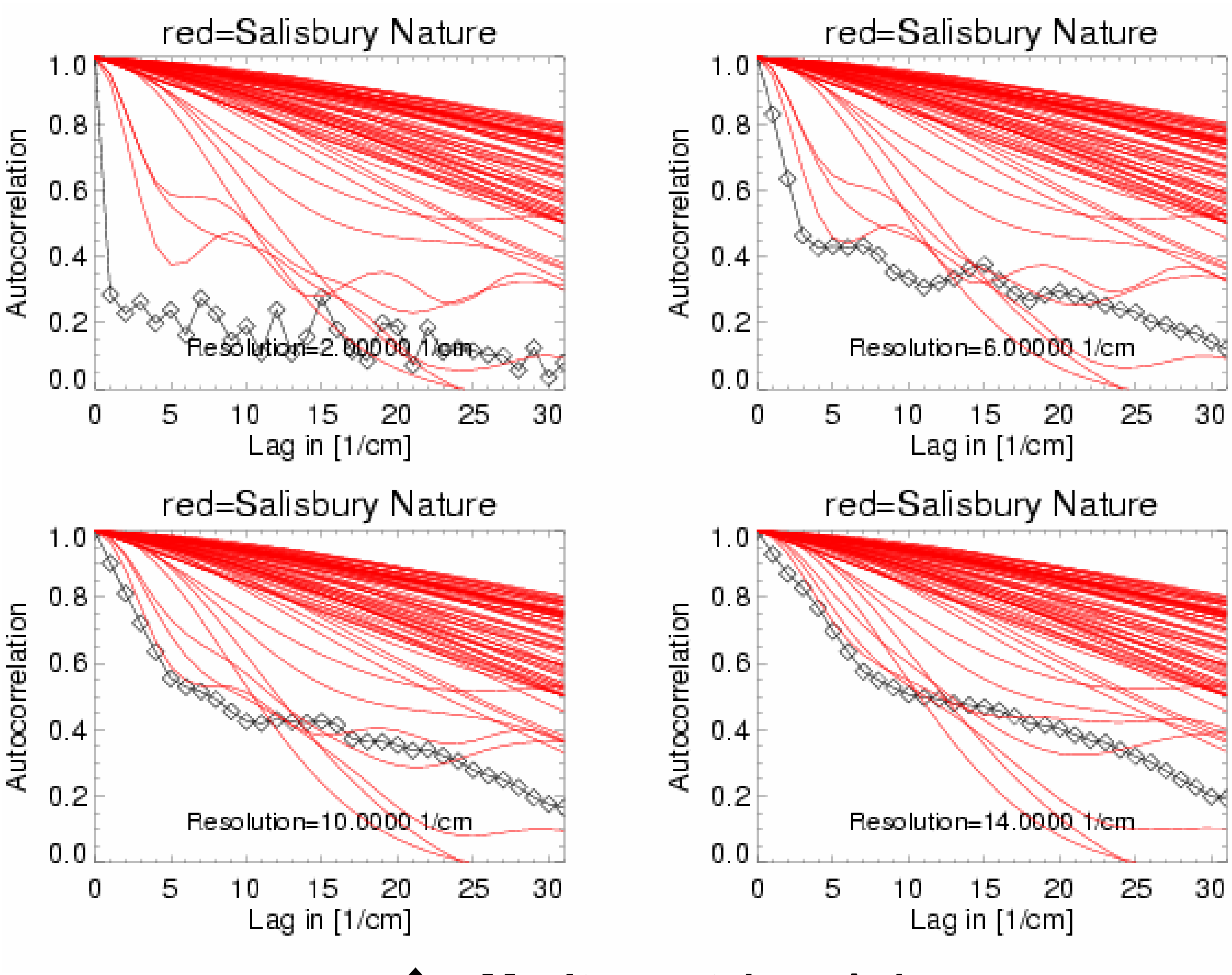
Autocorrelation function $P_x(L)$ of a sample population x as a function of lag L:

$$P_x(L) = \frac{\Sigma_{k=0}^{N-L-1}(x_k - \overline{x})(x_{k+L} - \overline{x})}{\Sigma_{k=0}^{N-1}(x_k - \overline{x})^2}. \tag{3}$$

Given the first few samples of $P_x(L), L = 0, 1, ..., L_{max}$ we calculate the average decorrelation wavenumber D_ν for a range of wavenumbers from L_{min} to L_{max} as:

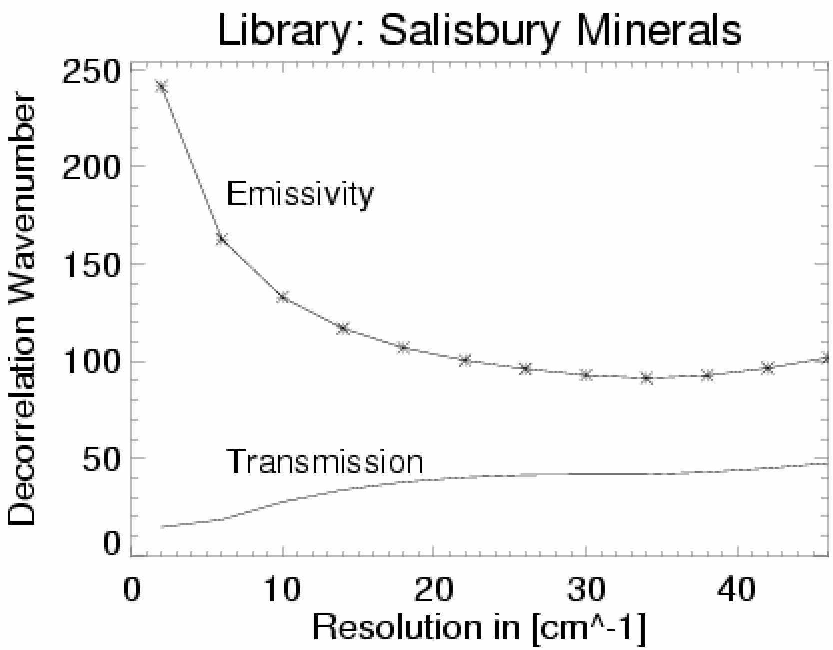
$$D_\nu = \frac{1}{L_{max} - L_{min} + 1} \sum_{L=L_{min},...,L_{max}} \frac{L}{P_x(0) - P_x(L)}. \tag{4}$$

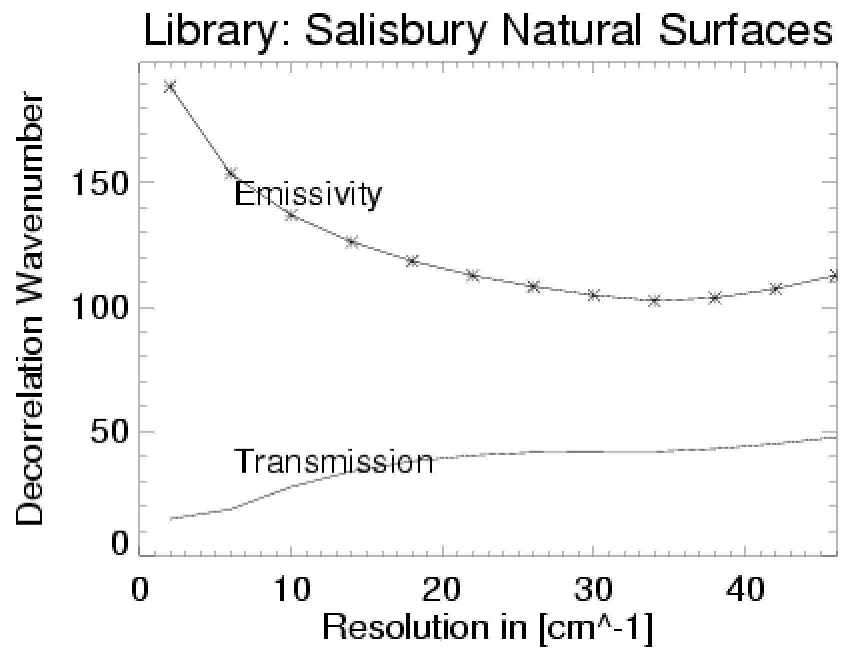
As a function of resolution



◇ =Modtran at 1 cm^-1

Emissivities are spectrally smooth





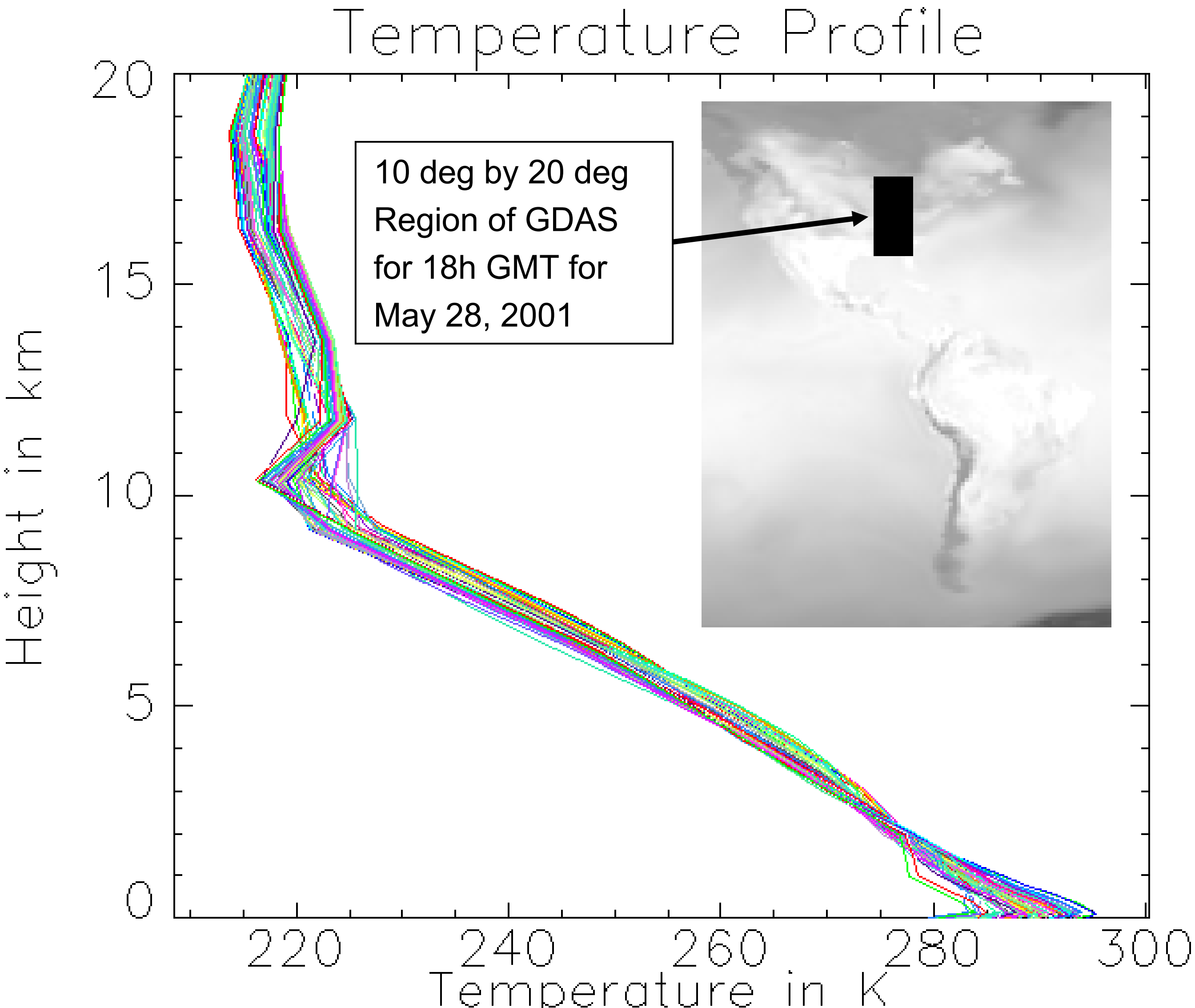
Result:

The decorrelation wavenumber for the emissivities is more than 100 cm^{-1} and almost constant for resolutions of 10 cm^{-1} or greater. $\Rightarrow$ need at least a resolution of 10 cm^{-1} or better to distinguish atmospheric spectral features from emissivity features.

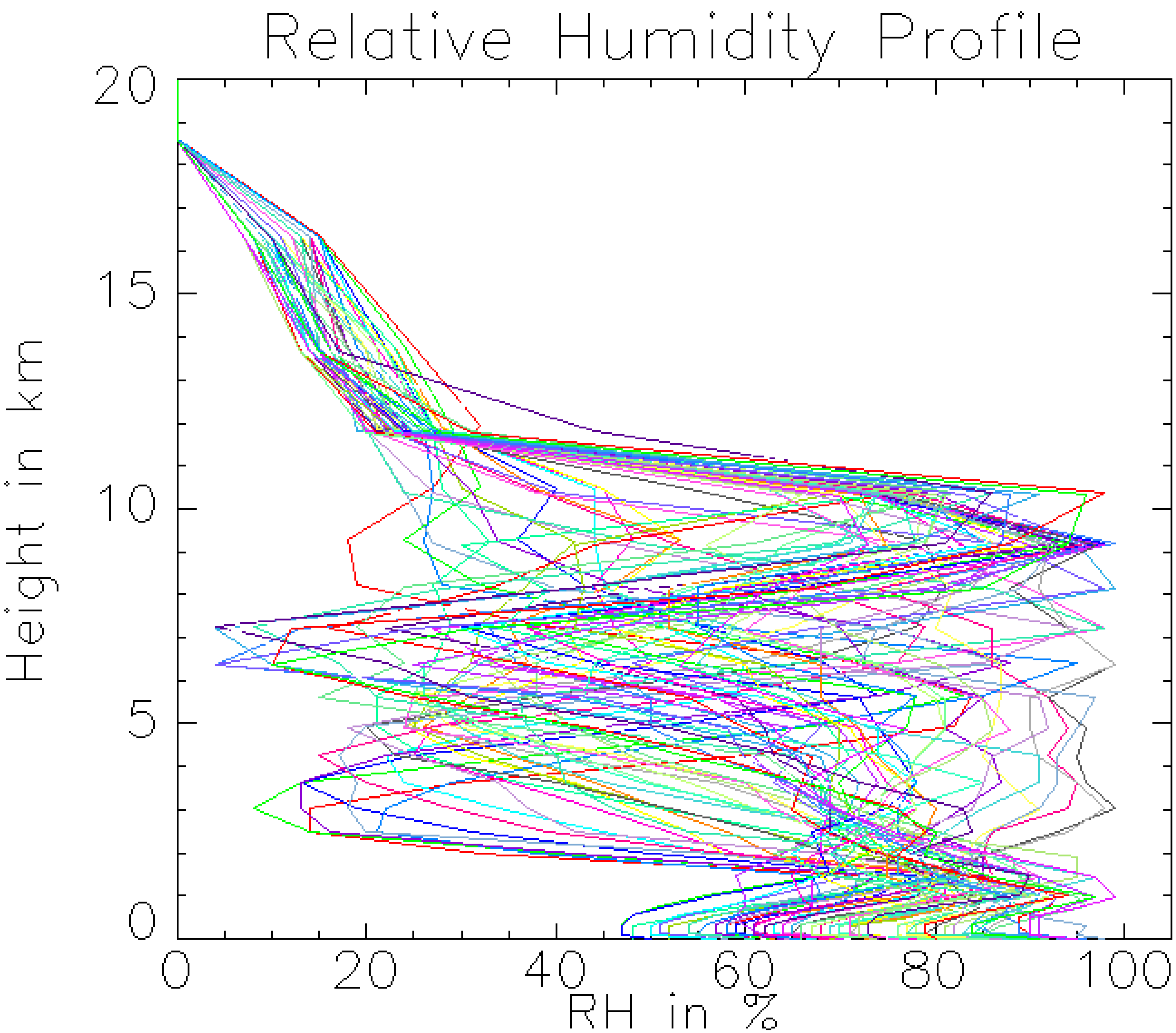
Why atmospheric correction?

- The atmosphere is highly variable in:
  - Water vapor
  - Temperature profile
- The sensor radiance is a function of atmospheric transmission, path radiance, down-welling radiance, ground temperature and emissivity
- Atmospheric correction attempts to retrieve emissivity and surface temperature
- Next pages show atmosphere for a region of 10 deg longitude times 10 degrees latitude for May 29, 2001 at 12 GMT

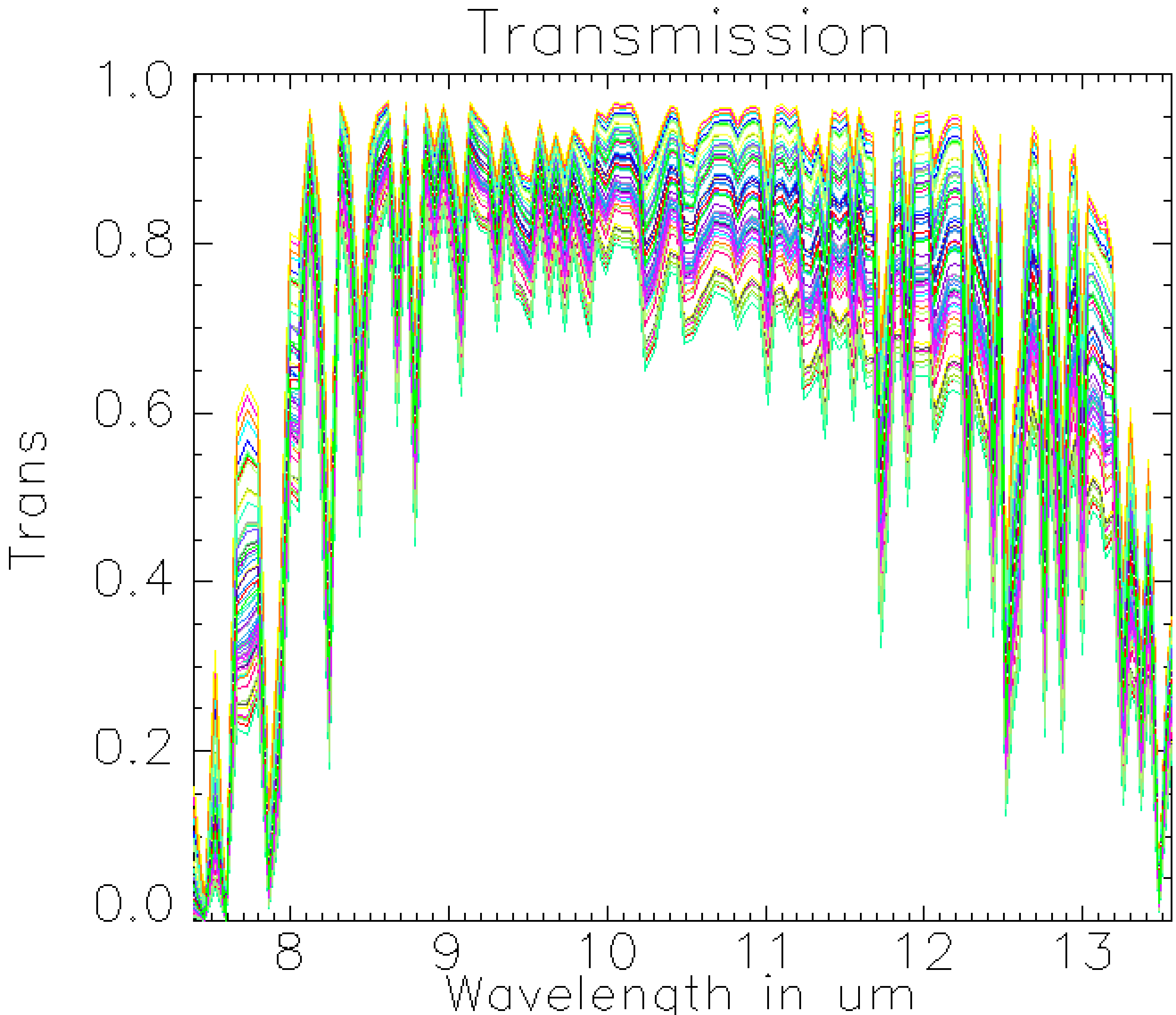
Temperature Profile



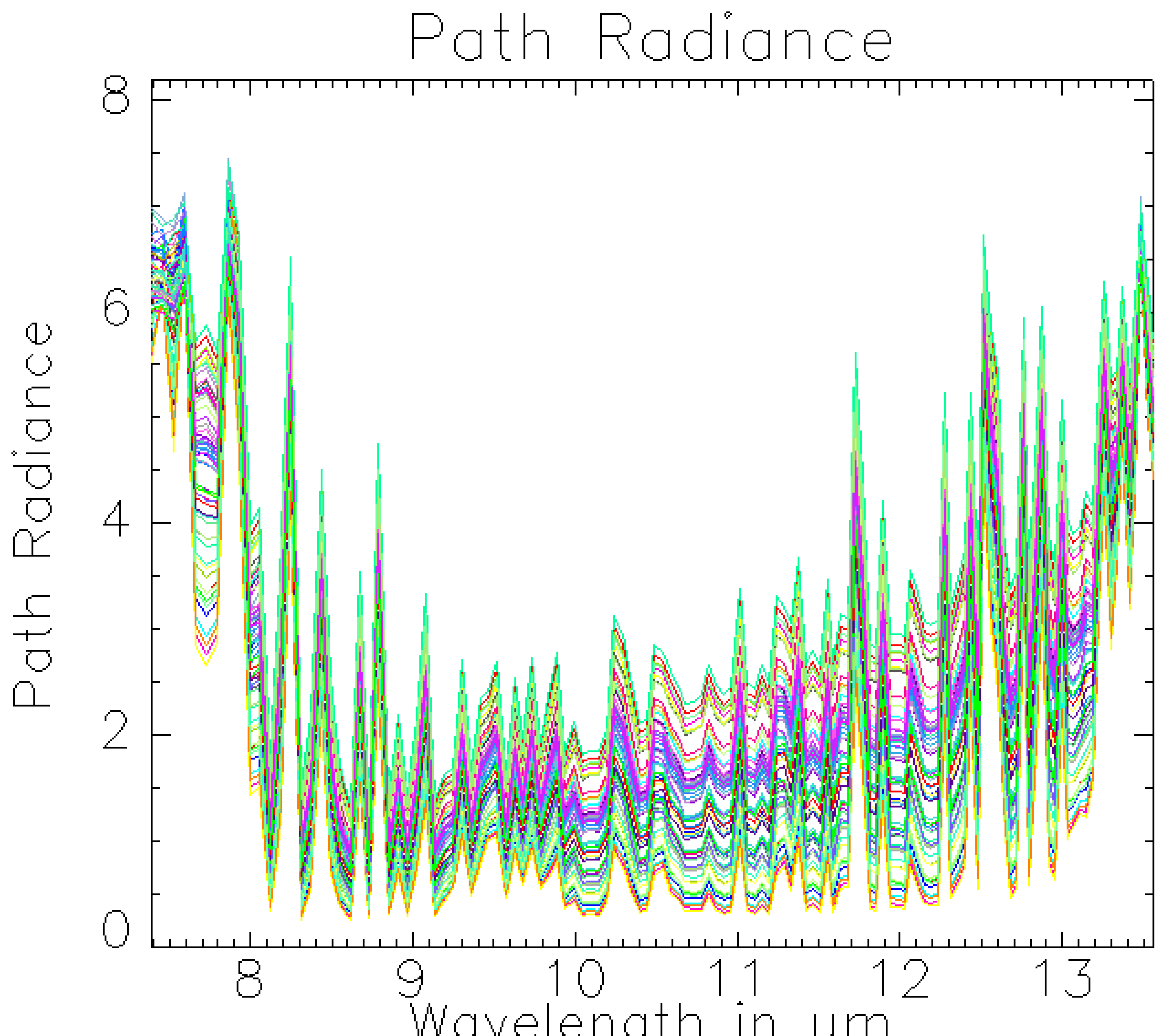
Relative Humidity Profile



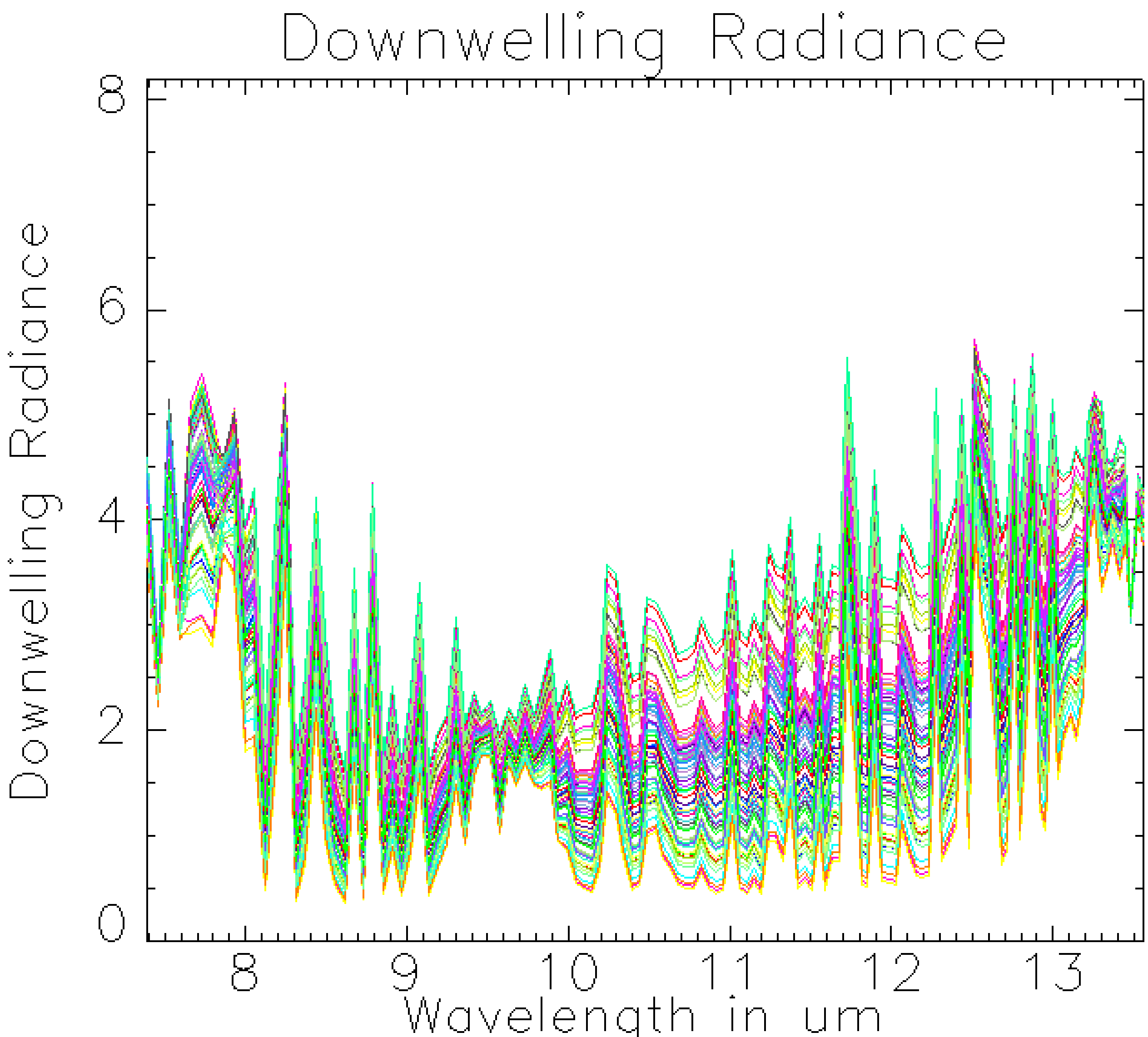
Transmission variation



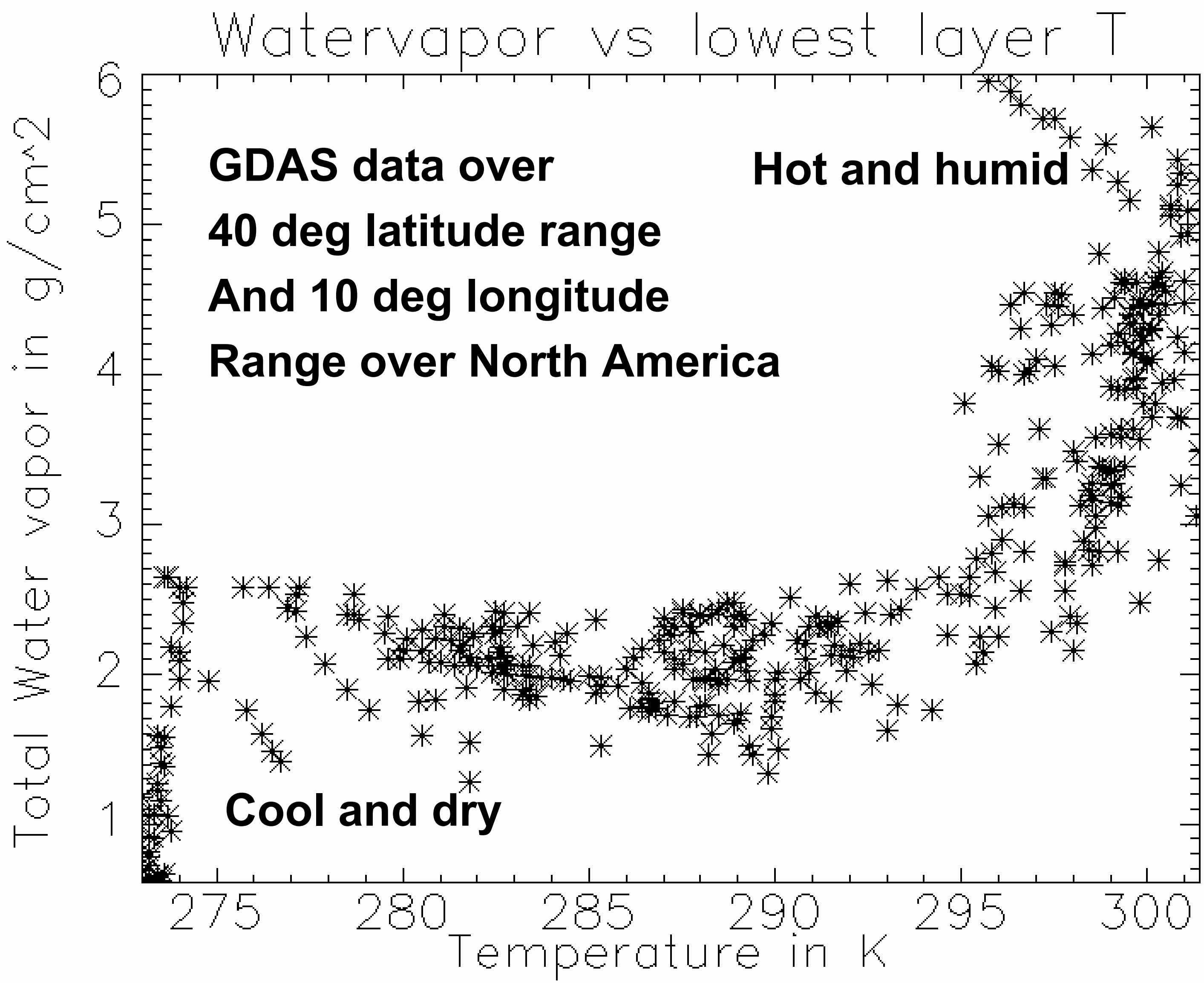
Path Radiance Variation



Down-welling Radiance



Correlation of temp and water vapor



New Temperature-Emissivity Separation (1)

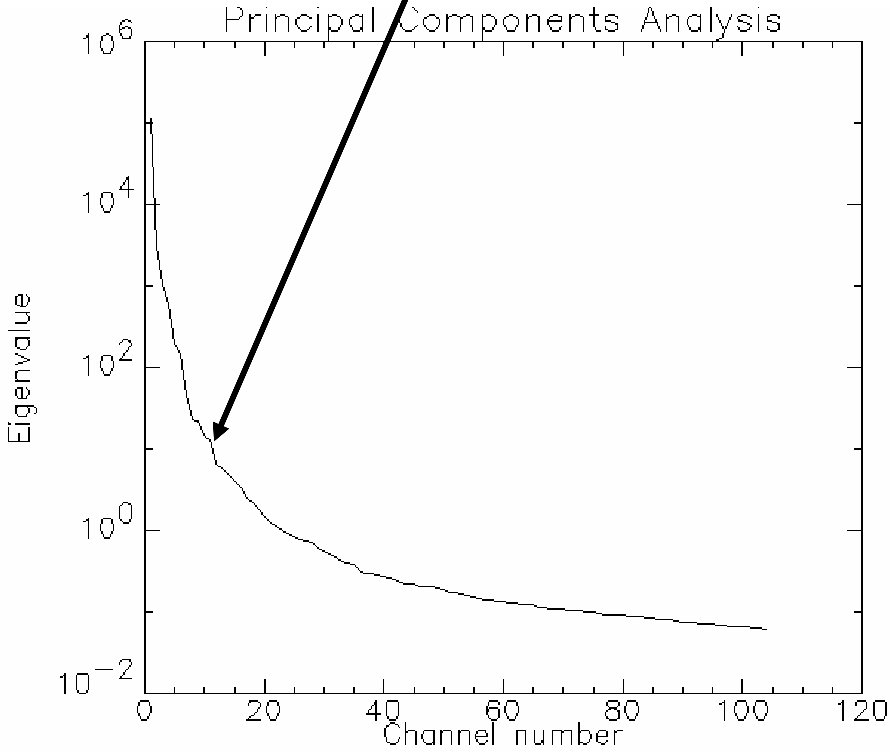
Algorithm:

1. Use the "In-scene Atmospheric Correction" (ISAC) method to get an estimate of transmission
2. Find best fitting atmosphere in look-up-table (LUT)
3. Compute the blackbody temperature T_bb in an atmospheric window from an atmospherically corrected surface radiance L_cor.
4. Compute emissivity: Emissivity=L_cor /B(λ,T_bb)
5. Try out different temperature offsets deltaT and re-compute emissivity iteratively.
6. Iterate 3-5 until emissivity has fewest atmospheric features or is smoothest.

What is the idea behind ISAC?

Images in the TIR are highly correlated, because Surface emissions are!

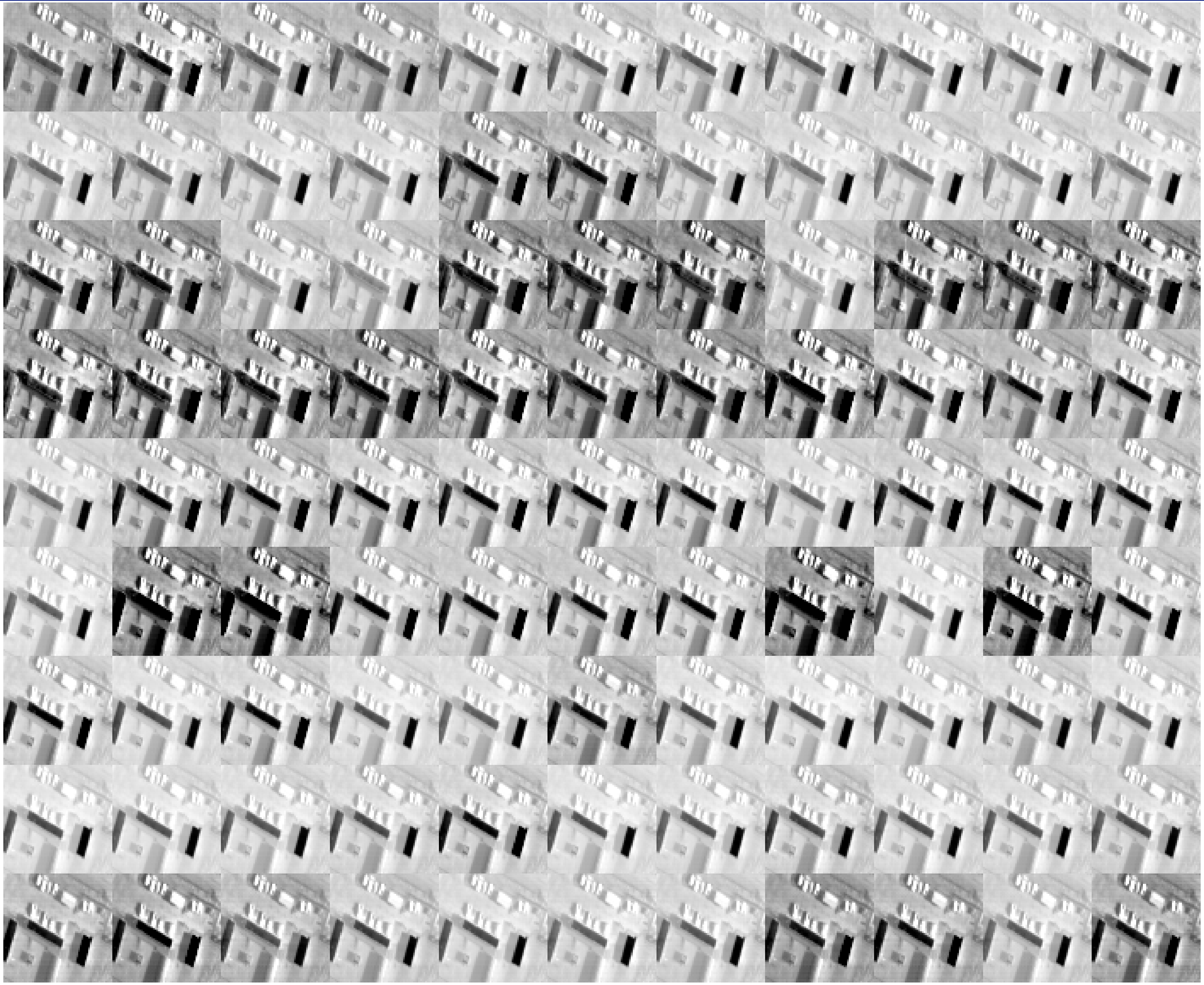
Number of channels with unique information



Radiance Cube

1

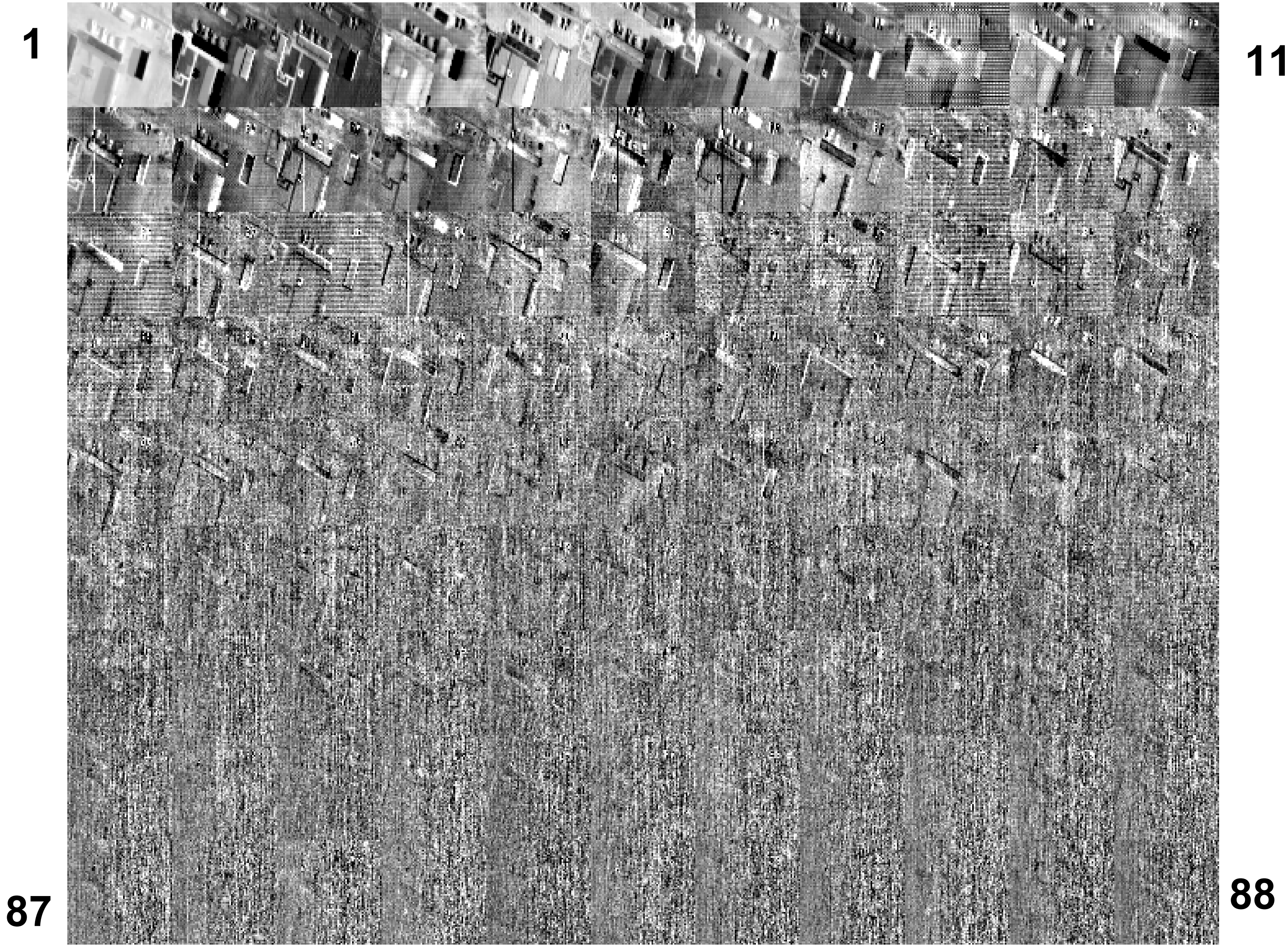
11



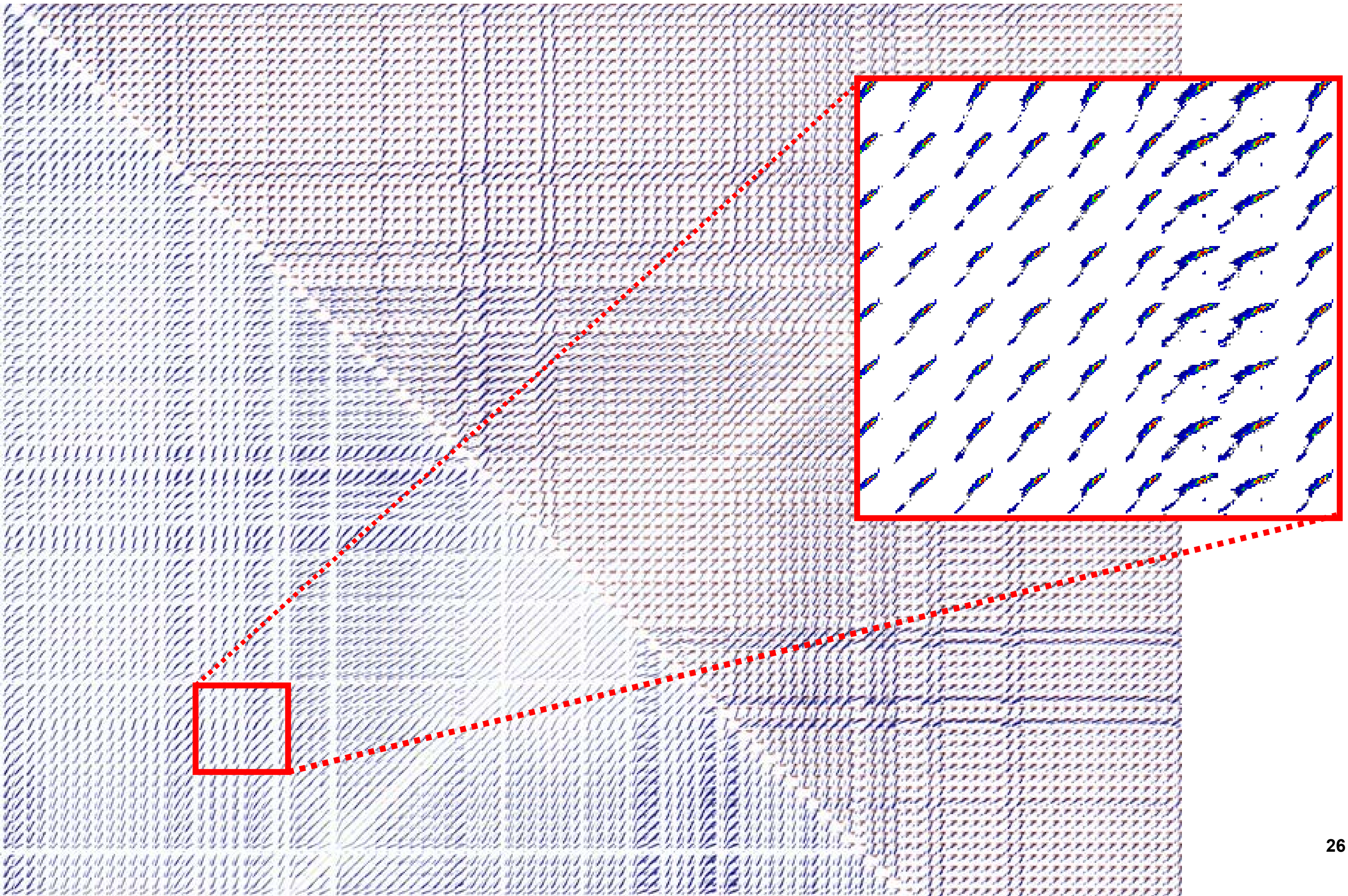
87

88

Principal components cube



2-D scatterplot of data

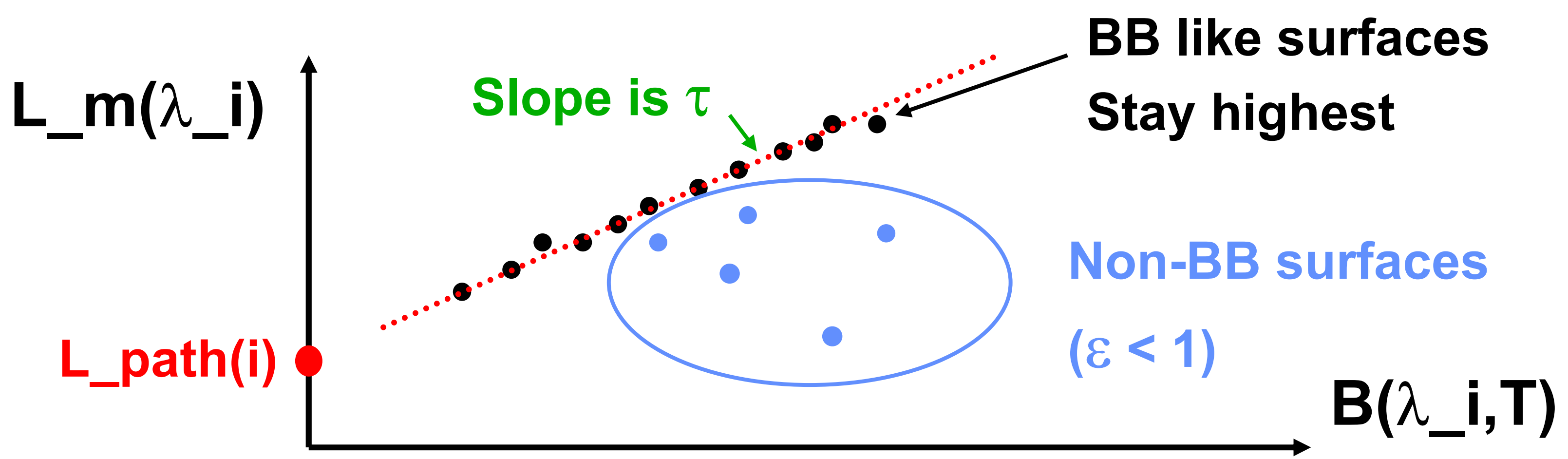


ISAC Algorithm - Aerospace

Assumptions:

- Atmosphere uniform over scene
- Surfaces present which have near blackbody ($\varepsilon \approx 1$) characteristics, e.g. water, vegetation,..:

$$L\_m(\lambda\_i)=B(\lambda\_i,T)\tau\_i+L\_path(i)$$



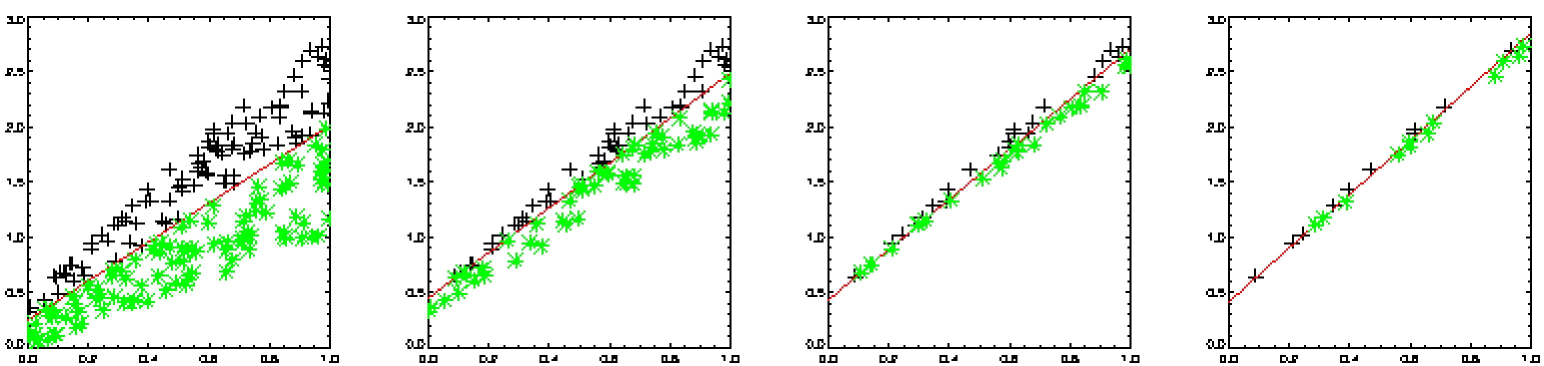
ISAC Algorithm steps

1. Select a reference wavelength λ_ref
2. For each pixel (n,m) compute the temperature T(n,m) at λ_ref
3. For each pixel perform a Kolmogorov-Smirnoff regression analysis for x_i=B(λ_ i,T) and y_i=L_m to find line y_i=a_i*x_i+b_i to fit highest points
4. Let the atmospheric transmission be: τ_i=p*a_i and the path radiance: L_path(λ_ I)=q*b_I, where p and q are scaling factors
5. Compute emissivity: ε=(L_m-L_path)/(B(λ_ i,T)* τ_i)

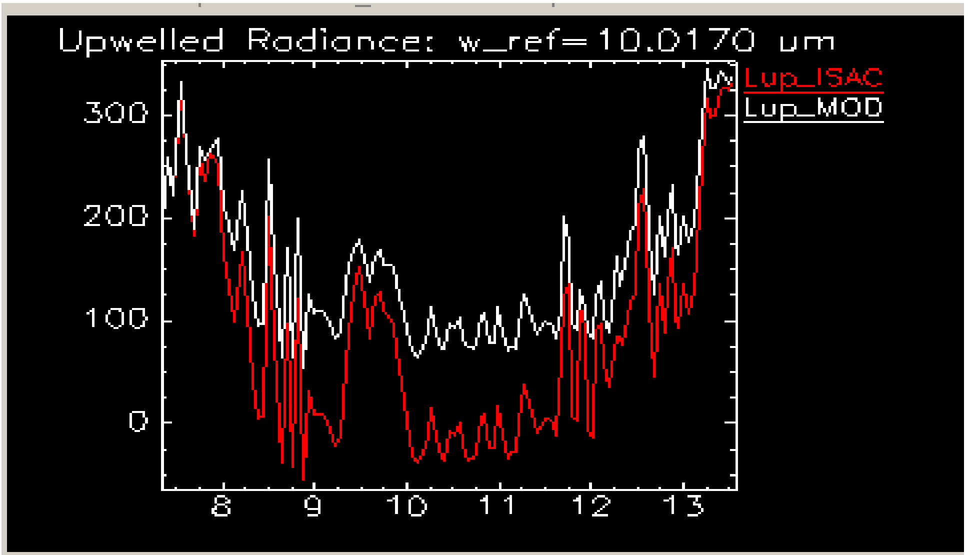
Quick ISAC implementation

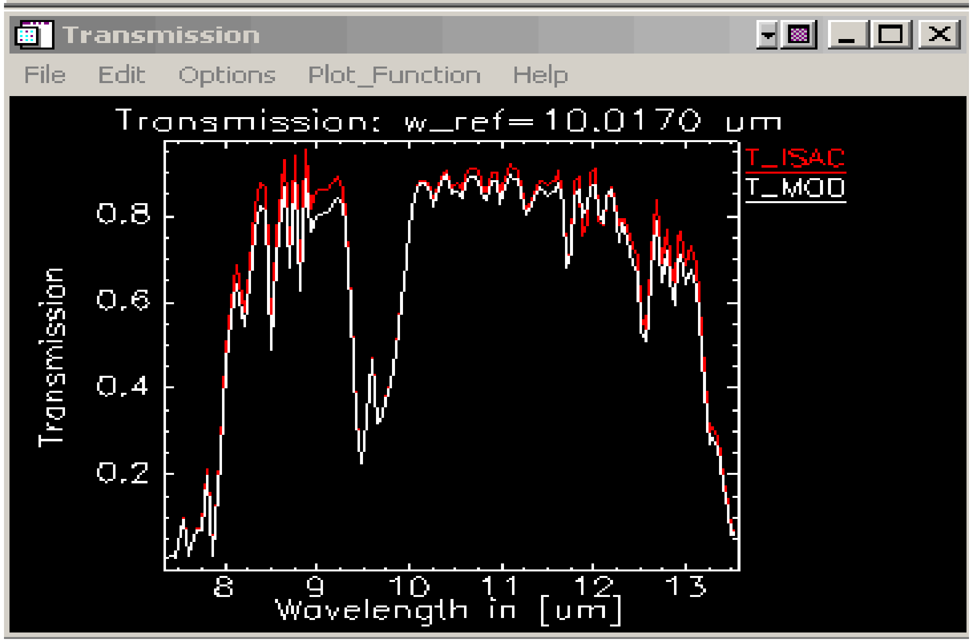
- Original ISAC method by Aerospace uses Kolmogorov-Smirnoff fitting of a 2-d scatterplot of the i-th channel radiance L(i) versus the Planck BB radiance L_ref(i)
- Easier and faster is the following method:

1. Fit a linear regression to points (x,y)=(L_ref(i),L(i))
2. Discard the points below the fit: L(x)=a*x+b
3. Repeat steps 1&2 for the points above the fit only until a fraction of points are left



ISAC result observations





Path radiance is not very close to the original

⇒Need a better method!

ISAC transmission is close to original:

τ ~P*τ_ISAC

⇒ Can use τ_ISAC in smooth Emissivity retrieval method!

Smooth emissivity retrieval method

Steps:

1. Compute the initial ($n = 0$) blackbody temperature $T_{bb,n}$ in an atmospheric window from an atmospherically corrected radiance $L_{cor,0}$:

$$T_{bb,n} = B^{-1}\left(\lambda_{window}, L_{cor,n}\right)$$

with

$$L_{cor,n} = \frac{L_{total} - L_{path\uparrow}(CW, T_{atmo}) - L_{path\downarrow}\varepsilon(n)}{\varepsilon(n)\tau_{atmo}(CW)},$$

where CW stands for column water, T_{atmo} is the effective atmospheric temperature and $\varepsilon(0) = 0.95$.

2. Compute spectral emissivity: $\varepsilon(n) = L_{cor,n}/B(\lambda, T_{bb,n}), n = 1, 2, ..$

3. Vary the surface temperatures $T_{bb,n} = T_{bb,0} + i\Delta T$, $i = 1, 2, ...,$ change the columnar water amounts and the effective atmospheric temperatures and recompute $\varepsilon(n)$ iteratively using steps 1-3.

4. Stop iteration when emissivity is smoothest, i.e. when

$$\sigma(\varepsilon(n)) = STDEV\left[\varepsilon_i(n) - \frac{1}{K}\sum_{j=i-K/2}^{i+K/2-1}\varepsilon_j(n)\right]_{i=K/2+1,...,M-K/2} = Min,$$

where the spectrum consists of M channels.

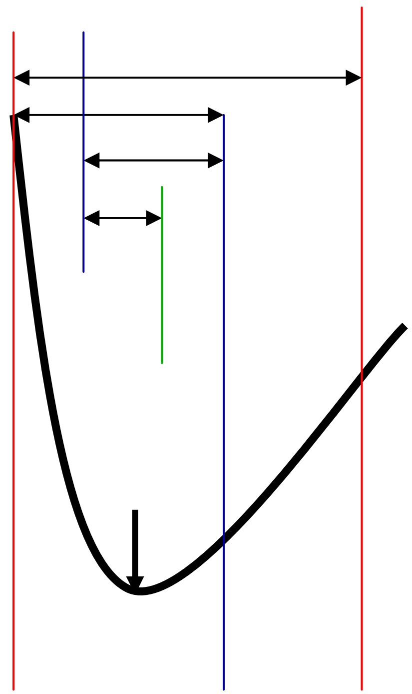
New implementation of the temperature search

Problem with linear search method:

- Accuracy determined by smallest step-size (e.g. 0.25 K for 75 K range)
- Need many function evaluations of smoothness (e.g. ~15000 for 300 steps)

Problem with Powell gradient search method:

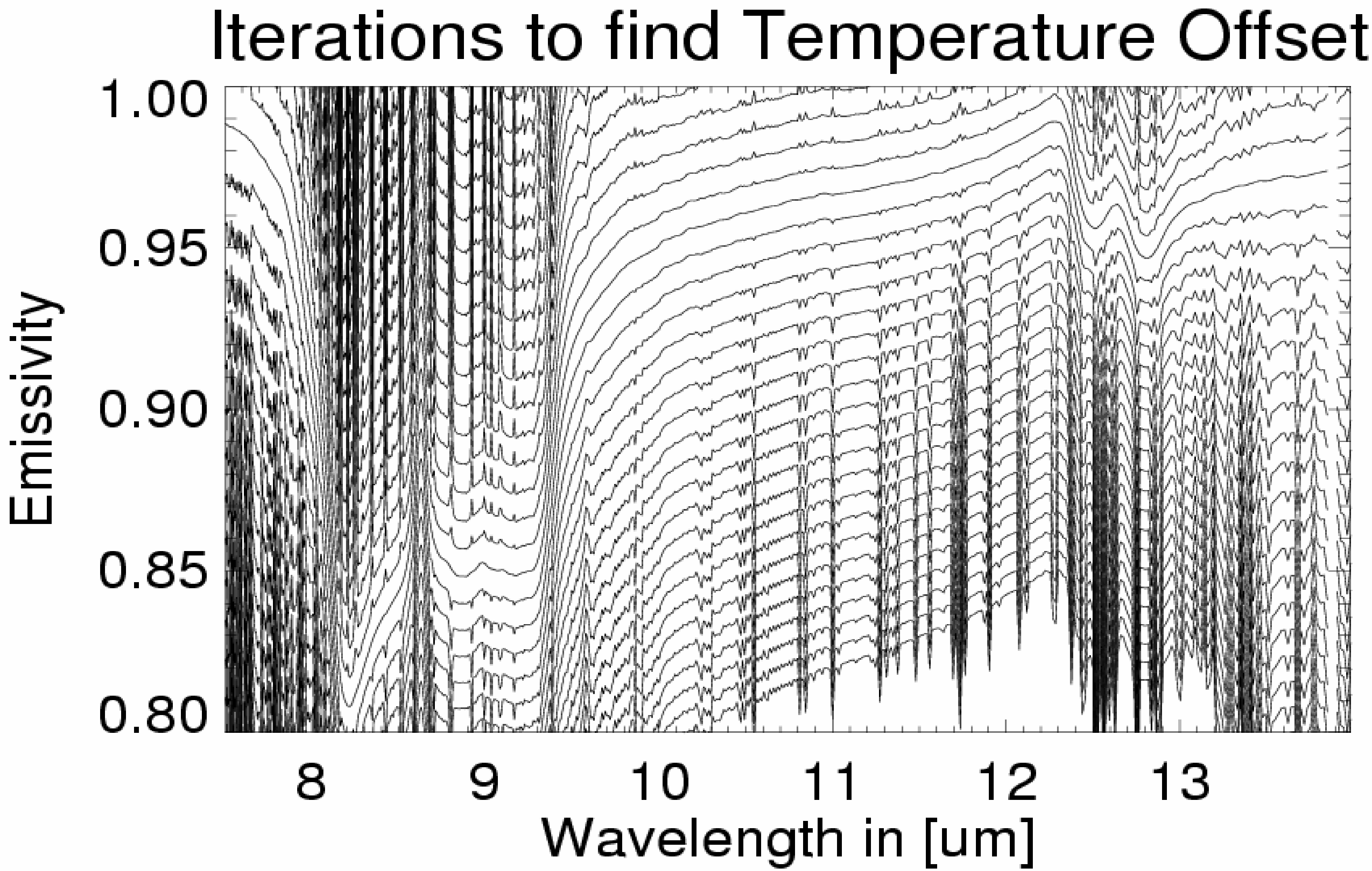
- Needs much larger # of function evaluations (IDL implementation ~80000 per pixel for Ftol=0.0001!)



Solution:

The simple Golden section search uses only about 1400 function evaluations – a savings of over 10 to linear search and 57 over gradient search method!

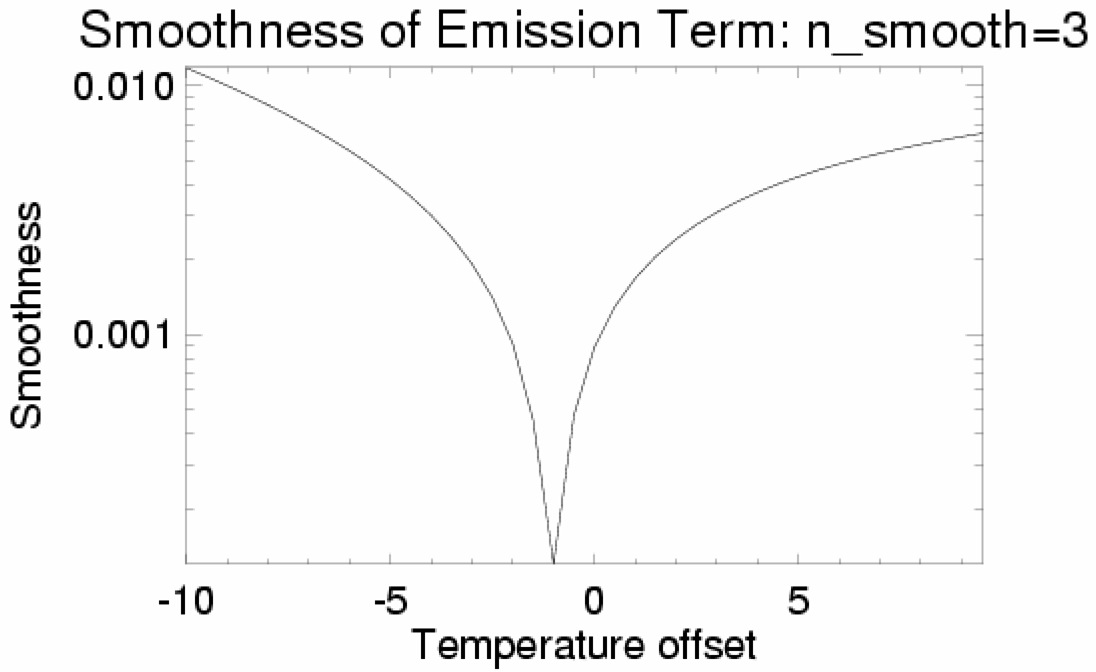
Iterative temperature retrieval



Retrieved emissivity as a function of temperature offset δT

Example of smoothness TES

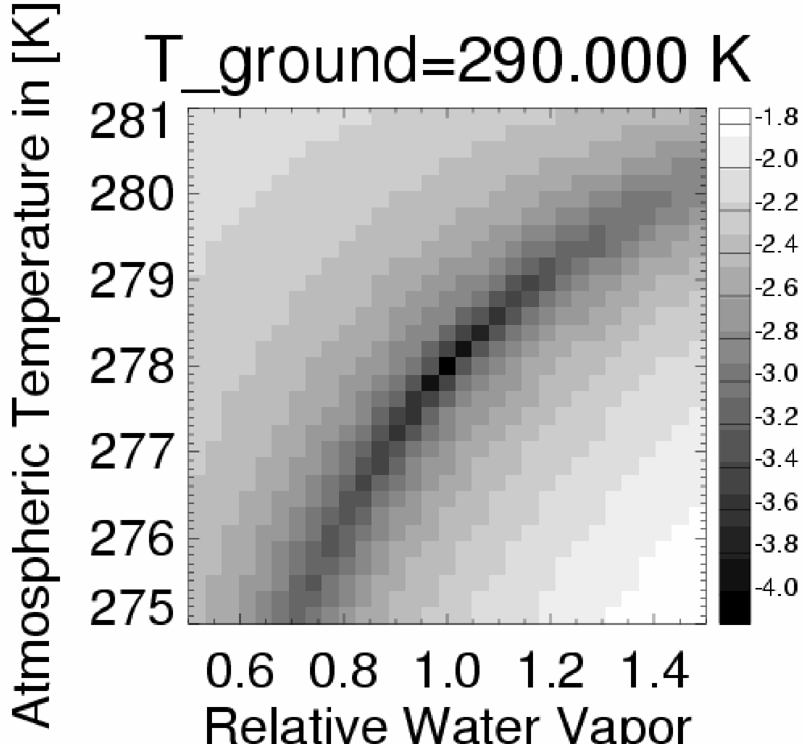
Emissivity smoothness as a function of surface temperature offset from the estimated ground:



Example result: true surface temperature was 290 K and the estimated temperature was 290.021. The RMS error of the emissivity in the region from 8.2 to 13 μm was 0.082.

Uniqueness problem?

2D result of the smoothness as a function of atmospheric temperature T_{atm} and relative water vapor content PW/PW_0 for Salisbury: *Soil USDA 87P706*:



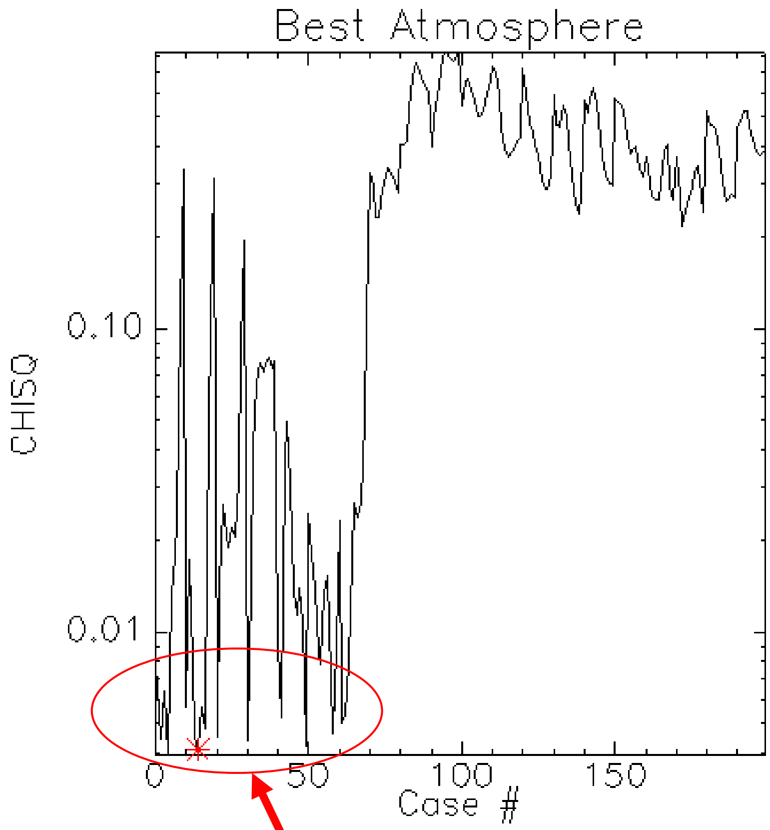
From Borel's 1996 paper
Using a simple 1-layer
Model for the atmosphere

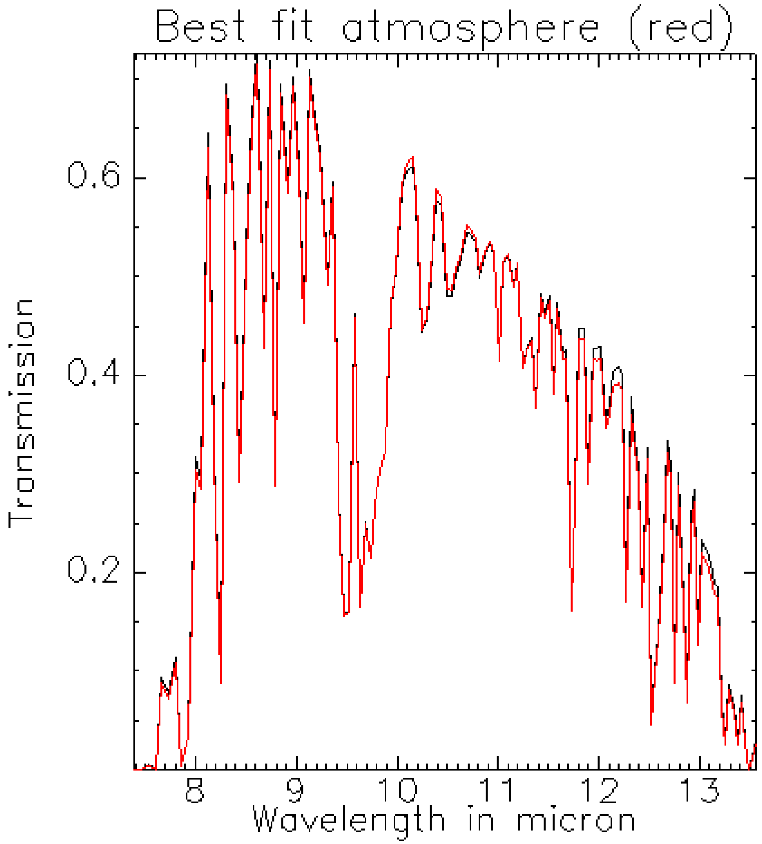
Discussion:

- There is a curved valley in which smooth emissivities can be retrieved.
- A sharp minimum (10^{-4} exists at $PW/PW_0 = 1$ and $T_{atm} = 278\ K$.
- Since the effective atmospheric temperature and column water vapor vary

Find best-fitting atmosphere

Compute Chi-Square between ISAC retrieved transmission and look-up table (GDAS based – works also with MOSESS db):

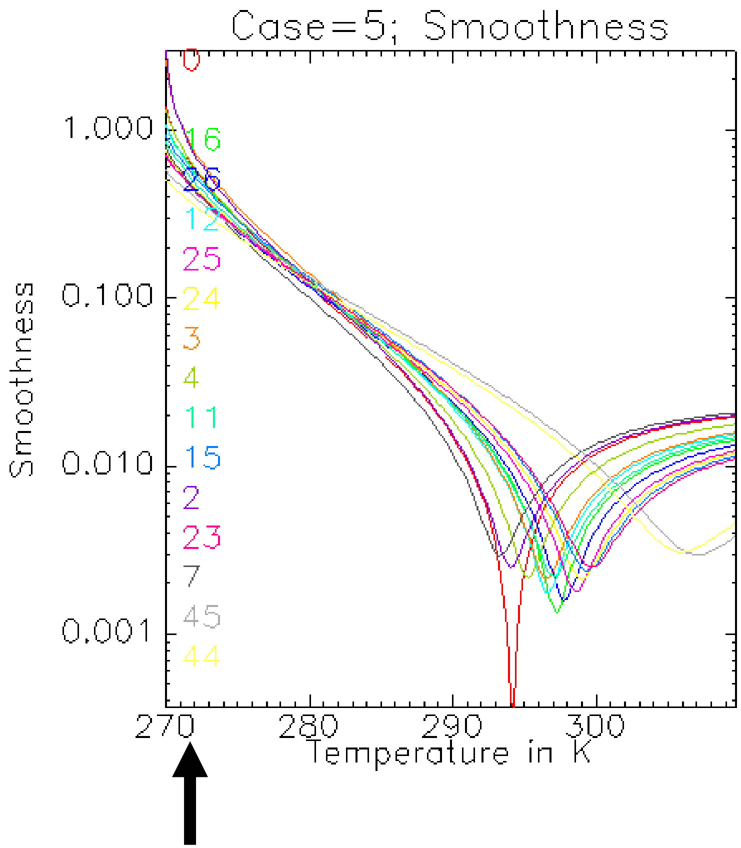


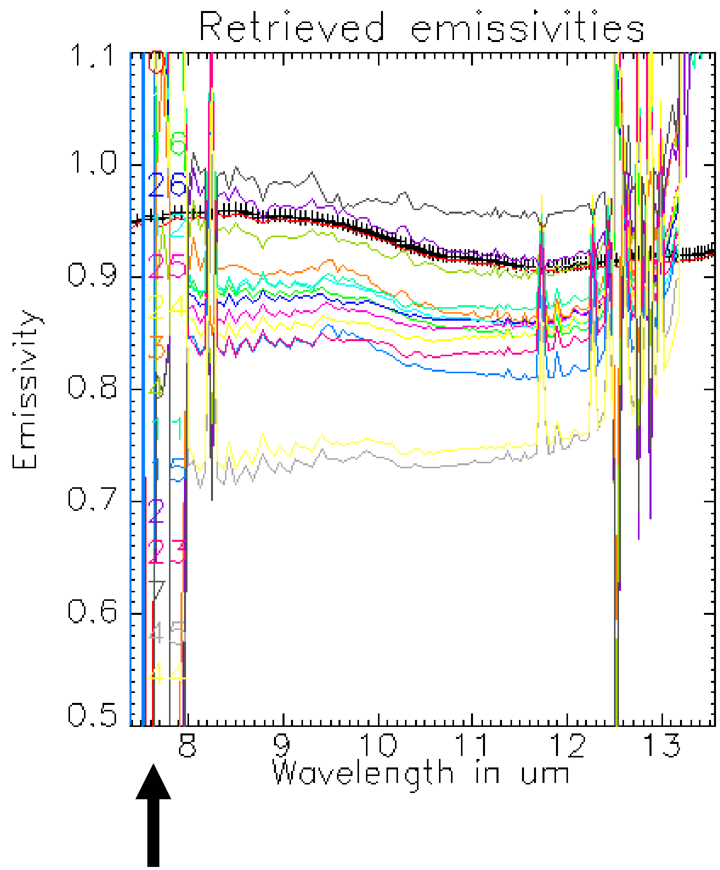


Uniqueness problem shows again!

Solving uniqueness problem by voting!

For a number of candidate atmospheres compute smoothness and retrieved emissivity and make the smoothest a winner:



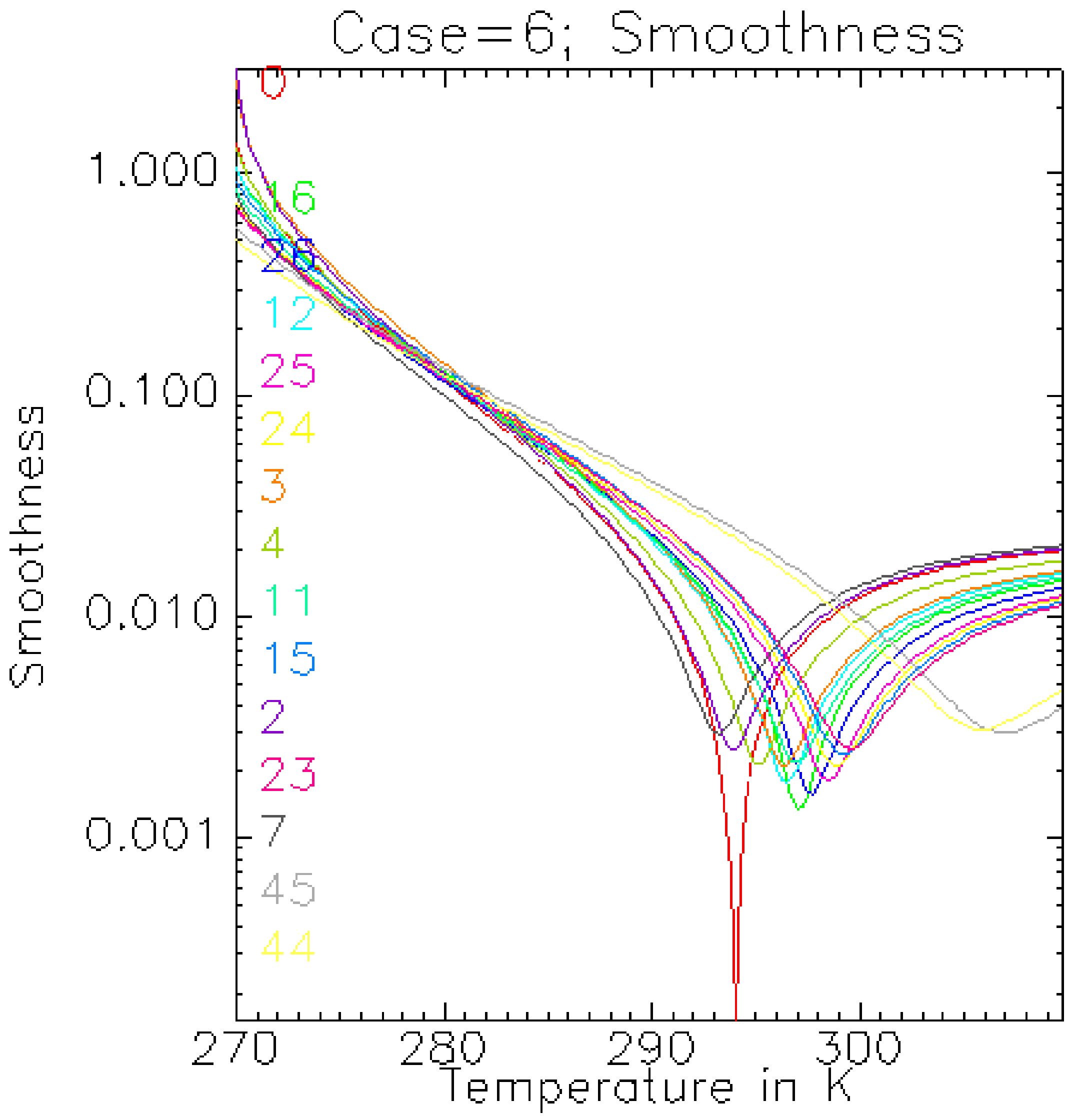


Atmosphere case#

Winner:Smoothest case in red

+++=original emissivity

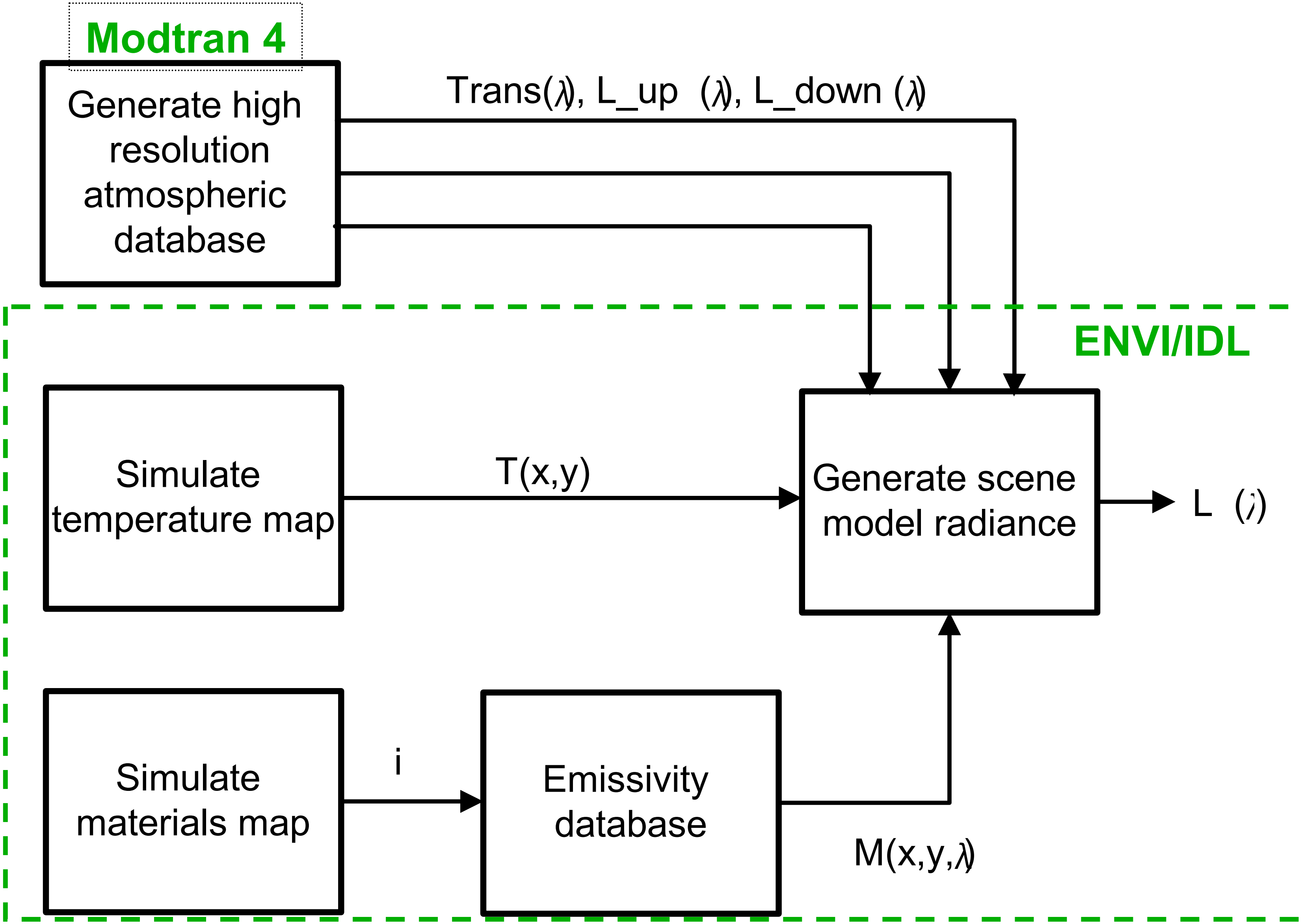
Does voting solve uniqueness problem?



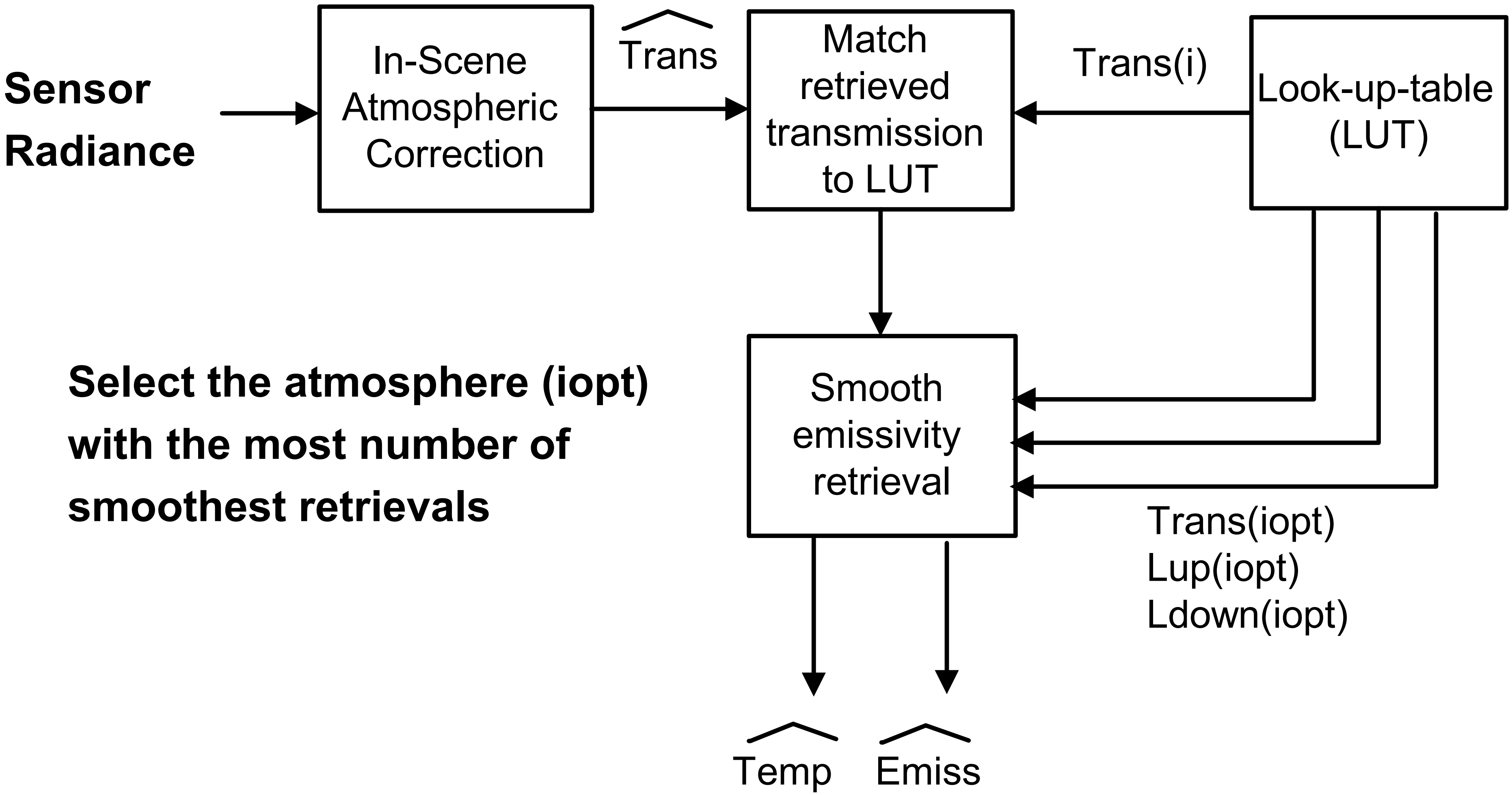
Observation:

Performing the smoothness test for many pixels (randomly or from clustering) leads to 2-3 top candidates for the atmosphere and usually picks the right one!

Scene Simulation



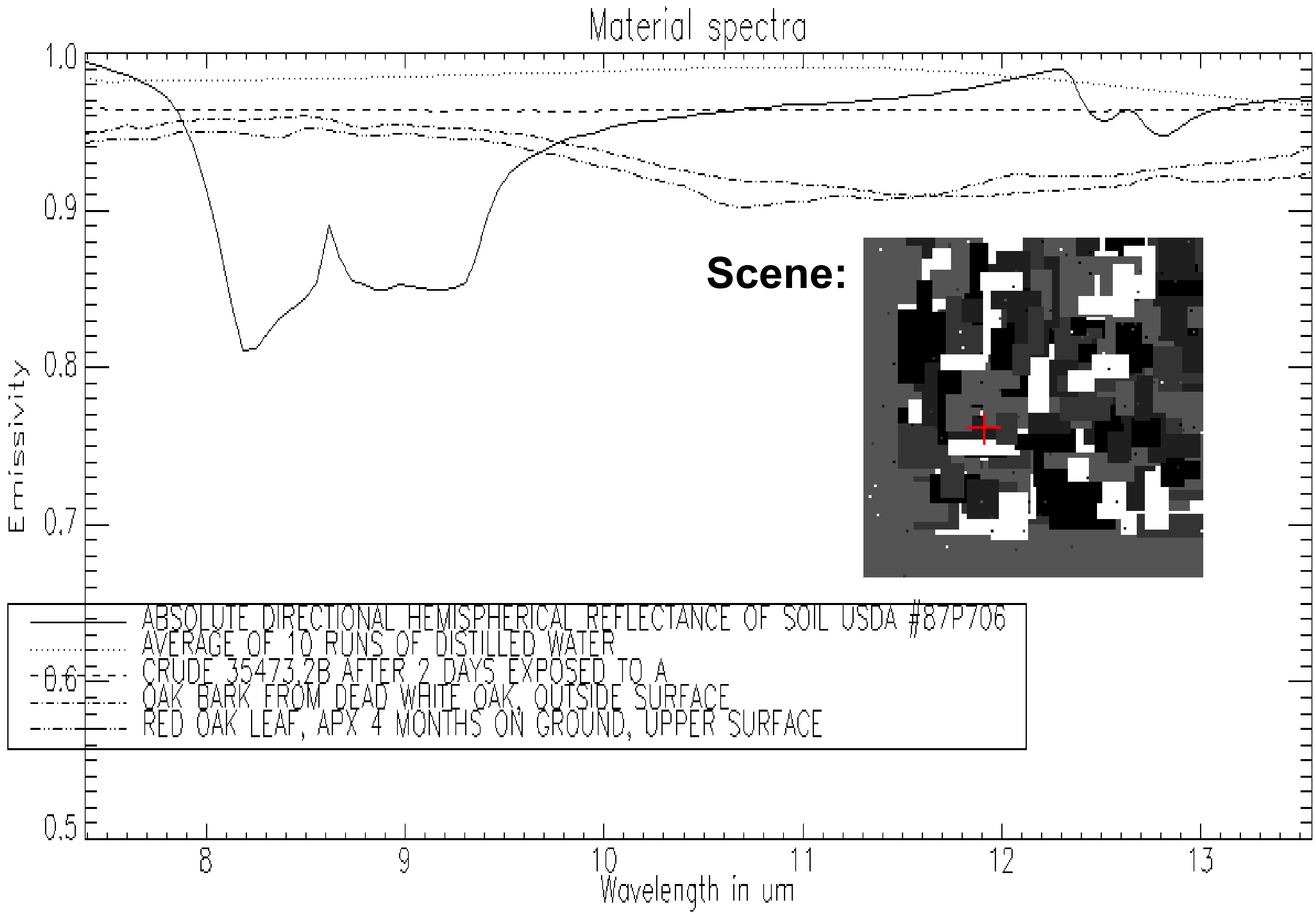
Combination of ISAC and smooth Emissivity retrieval



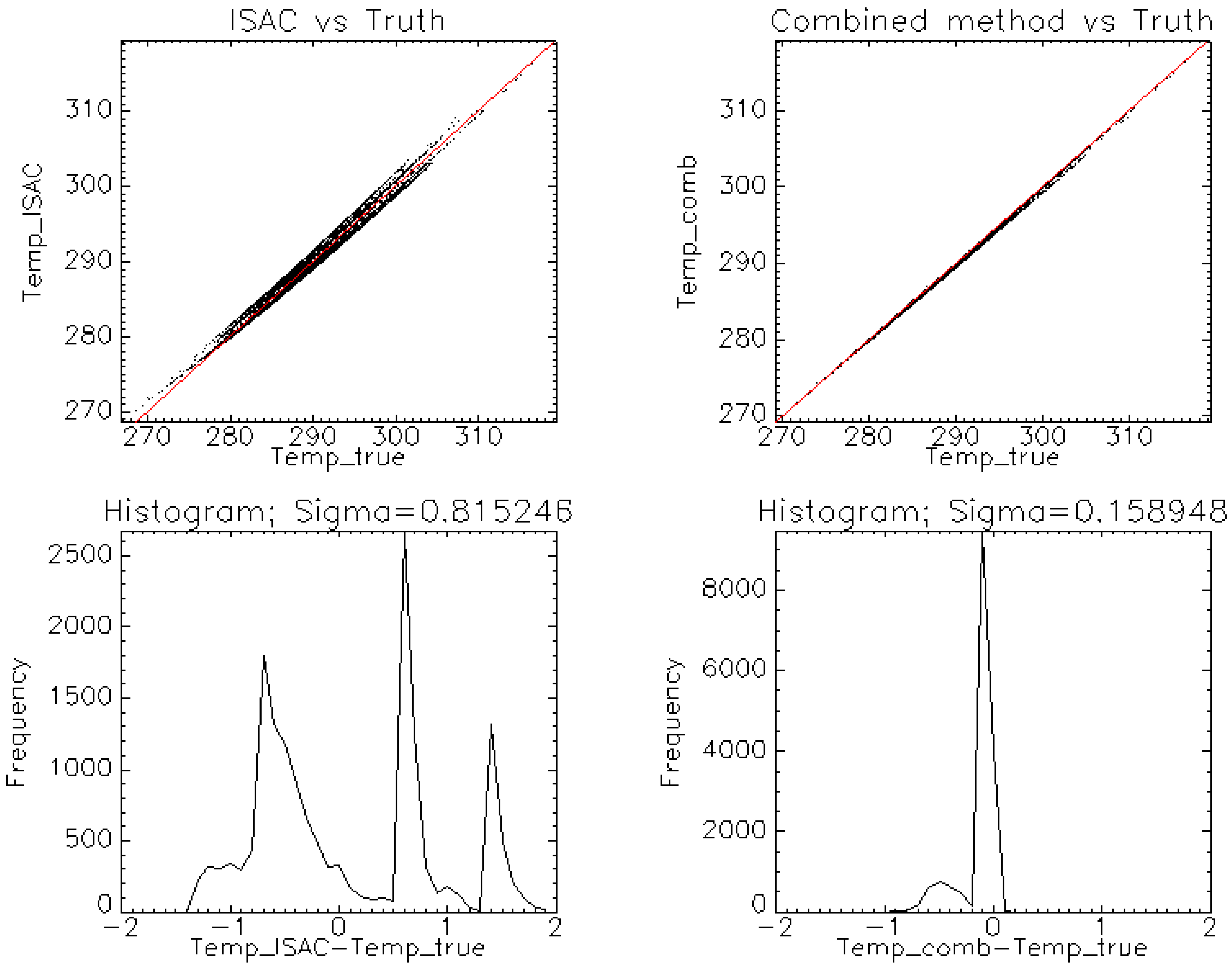
Select the atmosphere (iopt) with the most number of smoothest retrievals

Estimated temperature and emissivity

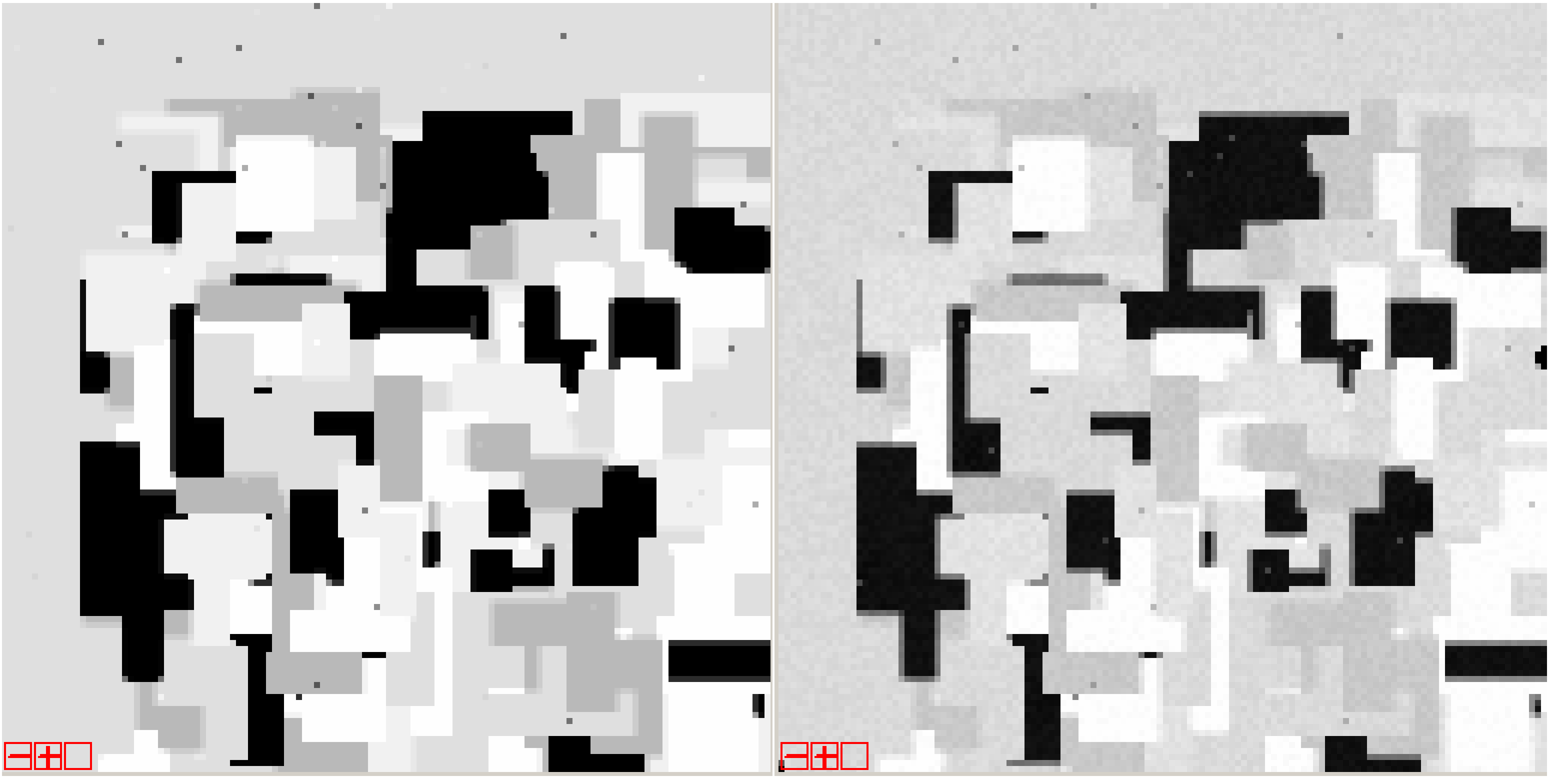
Simulated scene



Compare ISAC to new combined (ISAC+smoothness) method

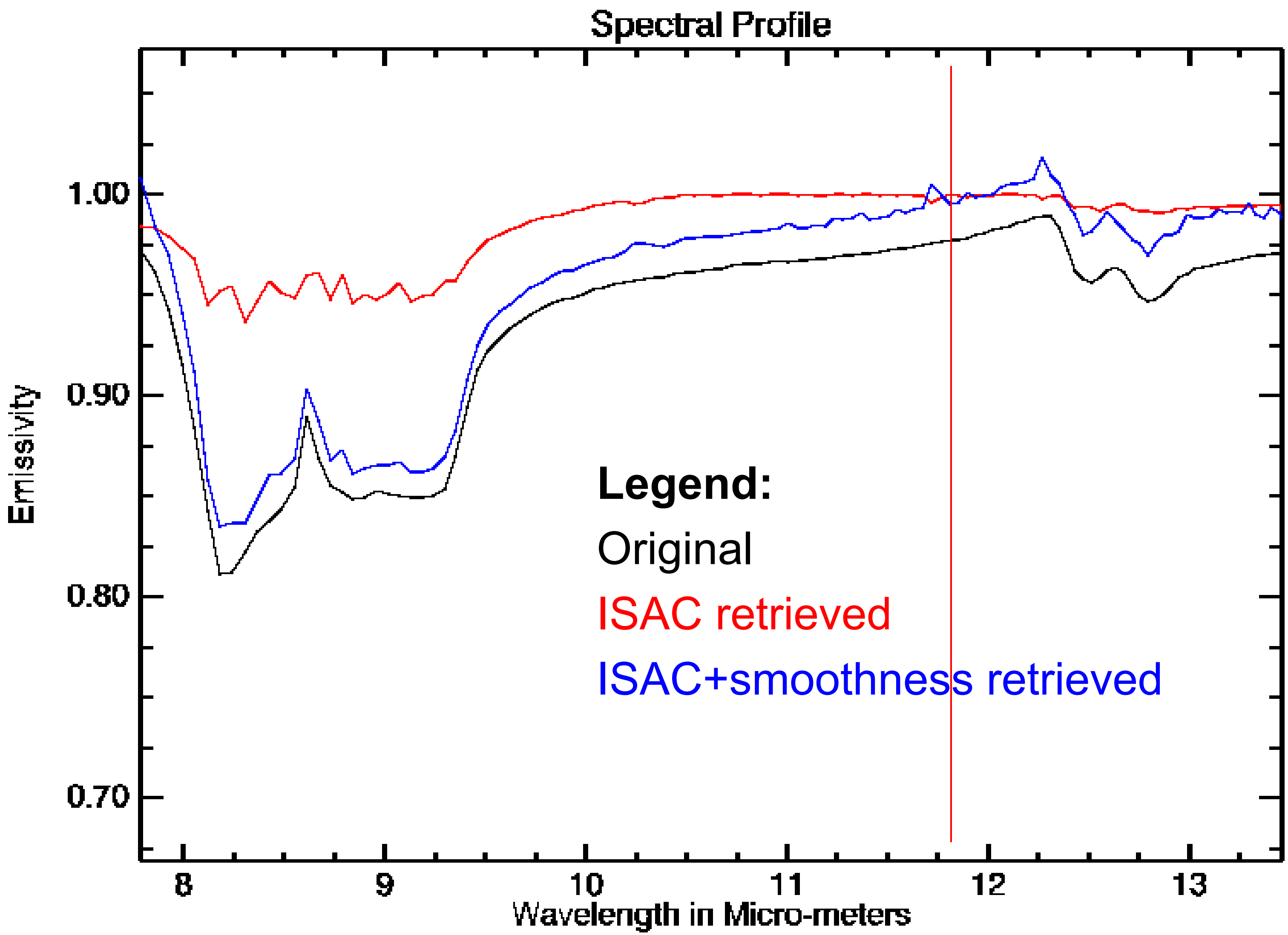


Compare original and retrieved emissivity

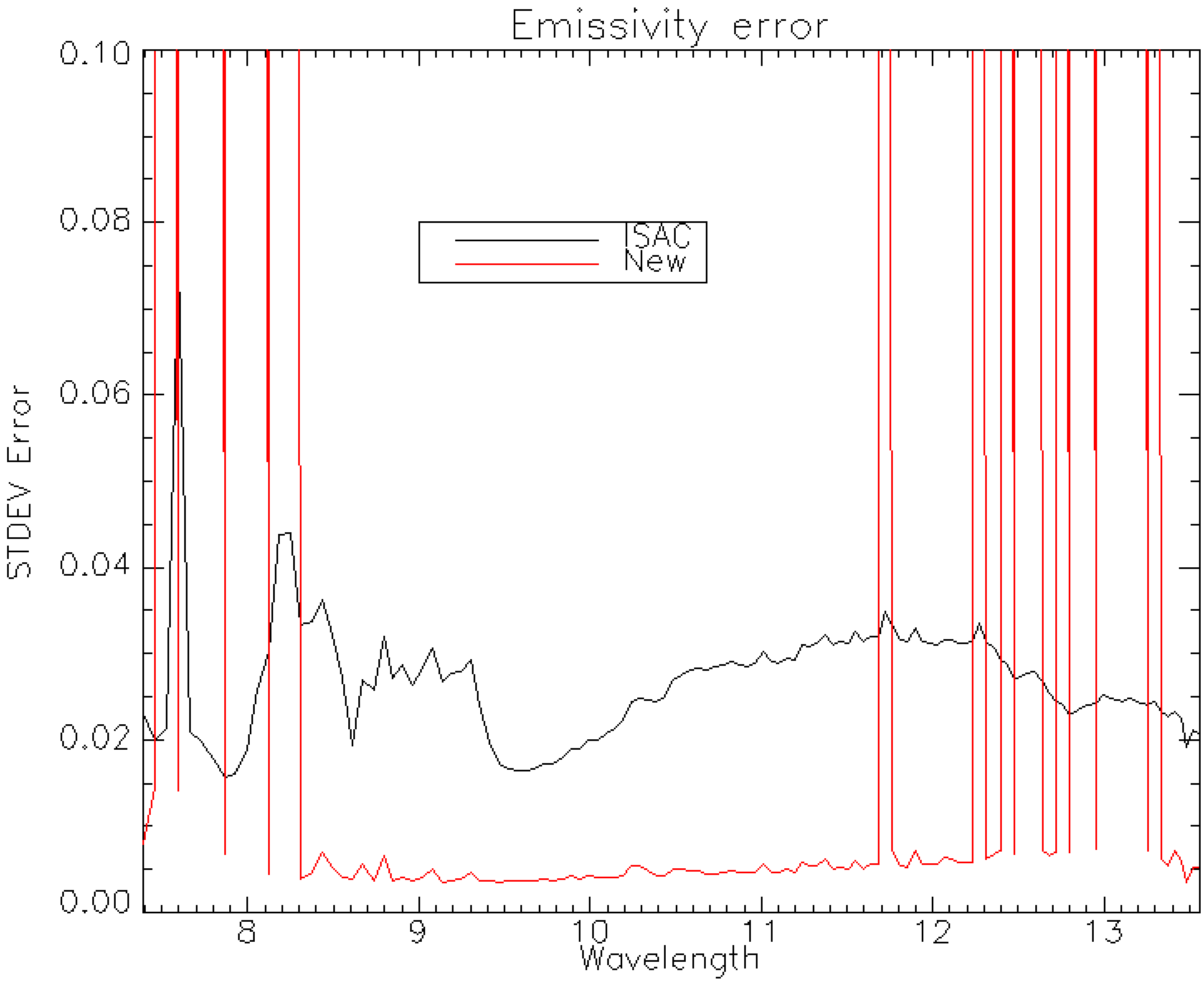


Channel at 8.31 micron

Emissivity for a single pixel

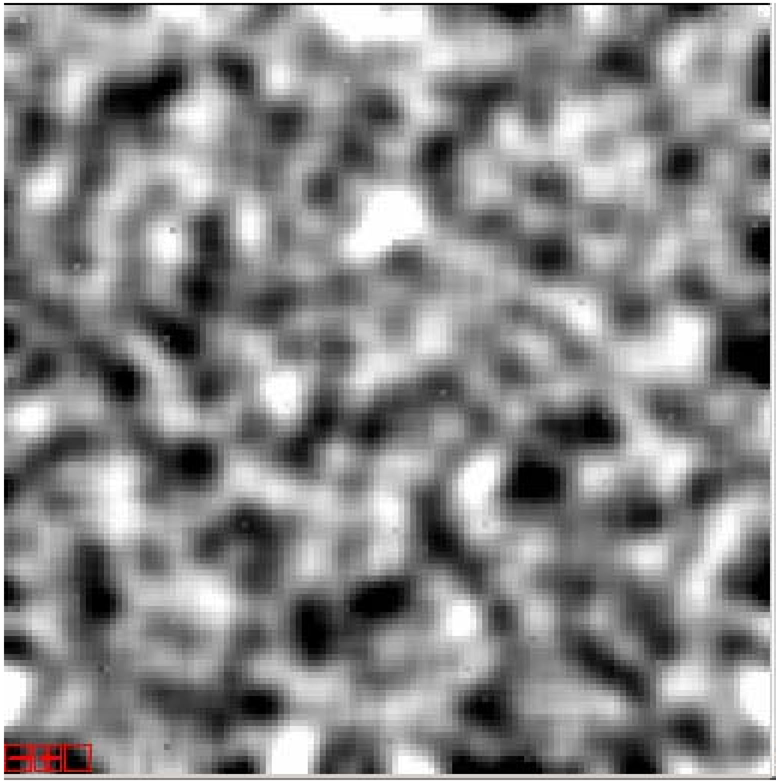


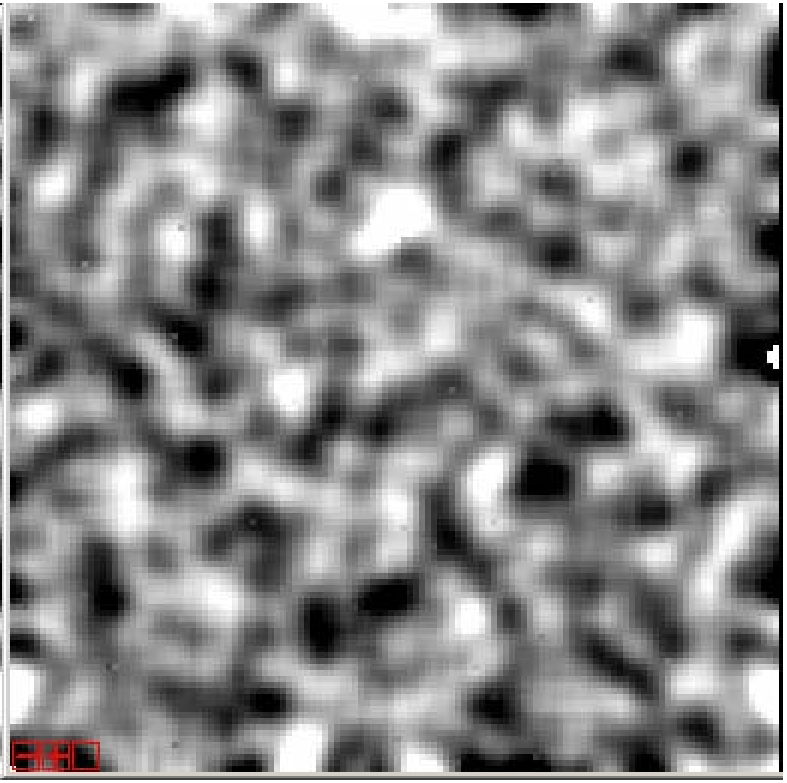
RMS Emissivity error



Temperature Map

Original **Retrieved**



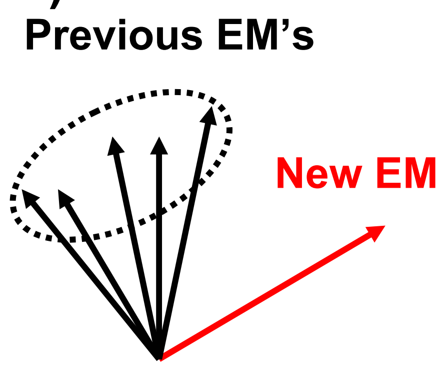


Fast spectral angle classification

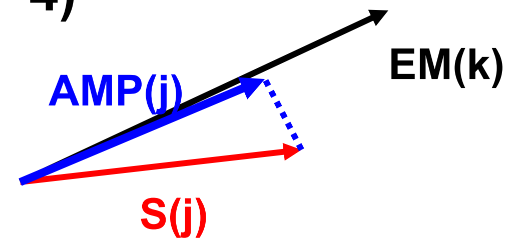
Algorithm:

1. Select a random spectrum and assign it as end-member 1: EM(1)=S(1)/|S(1)|; N=1
2. For all N spectra EM(i) compute cosine of spectral angle: CD(i,j)=EM(i)*S(j)/|S(j)|, i=1,…,N
3. If all CD(i,j), i=1,…,N less than CD(threshold) then assign new end-member EM(i+1)=S(j)/|S(j)| and N=N+1
4. Project pixel S(j) on best matching end-member k: AMP(j)=median(S(j)/EM(k)) where k is found by: CD(k,j)=min(CD)
5. Repeat steps 2-4 until all spectra are processed or a maximum number of end-member spectra is generated

3)



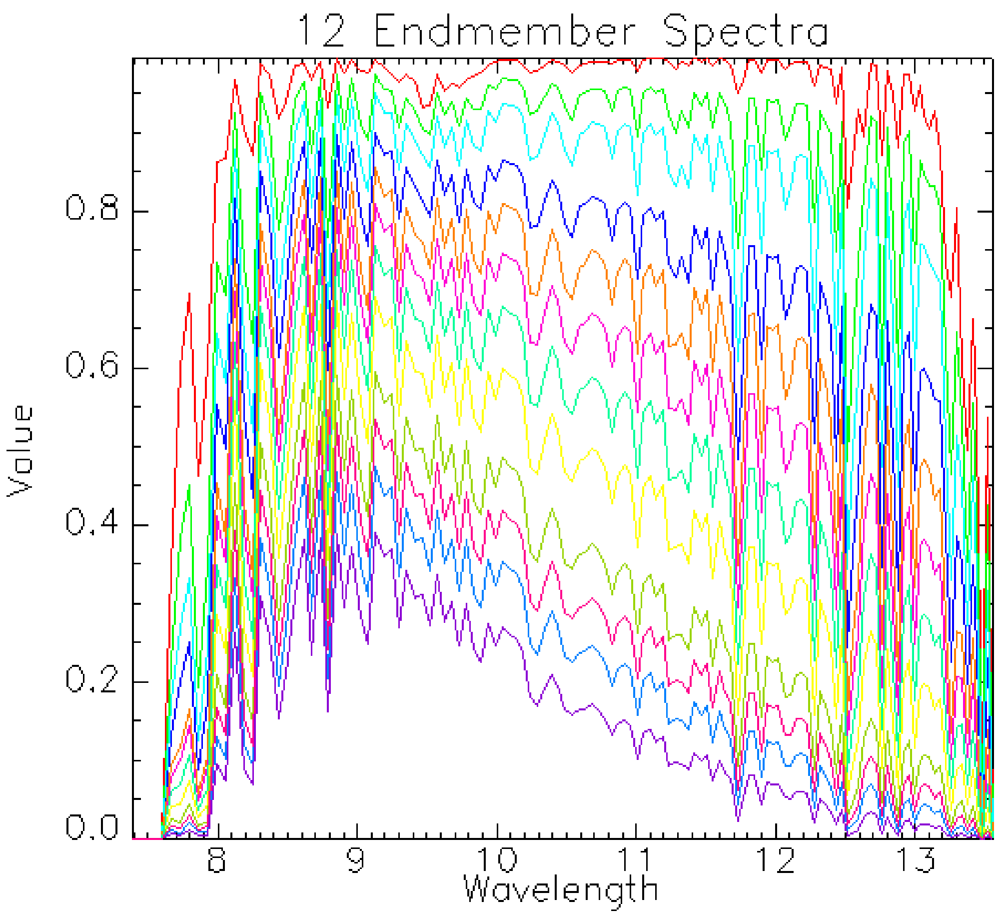
4)

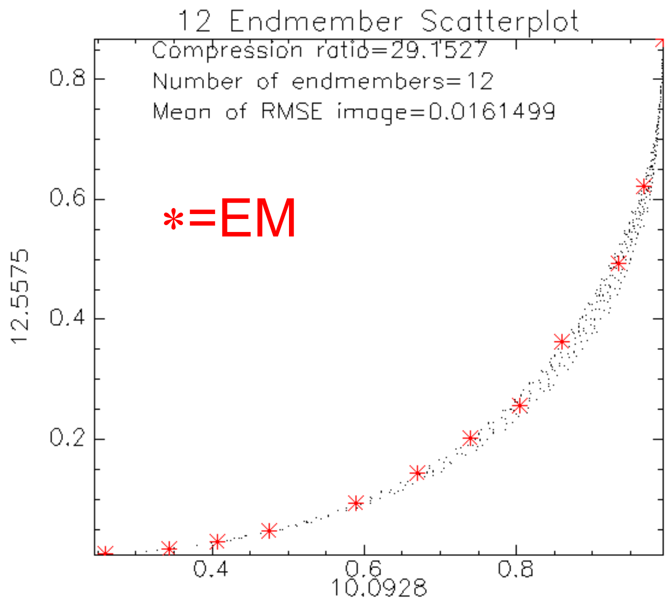


Compression of Look-up Tables

Modtran4 generated database using SSI Mkdbase program for MOSESS V1.3

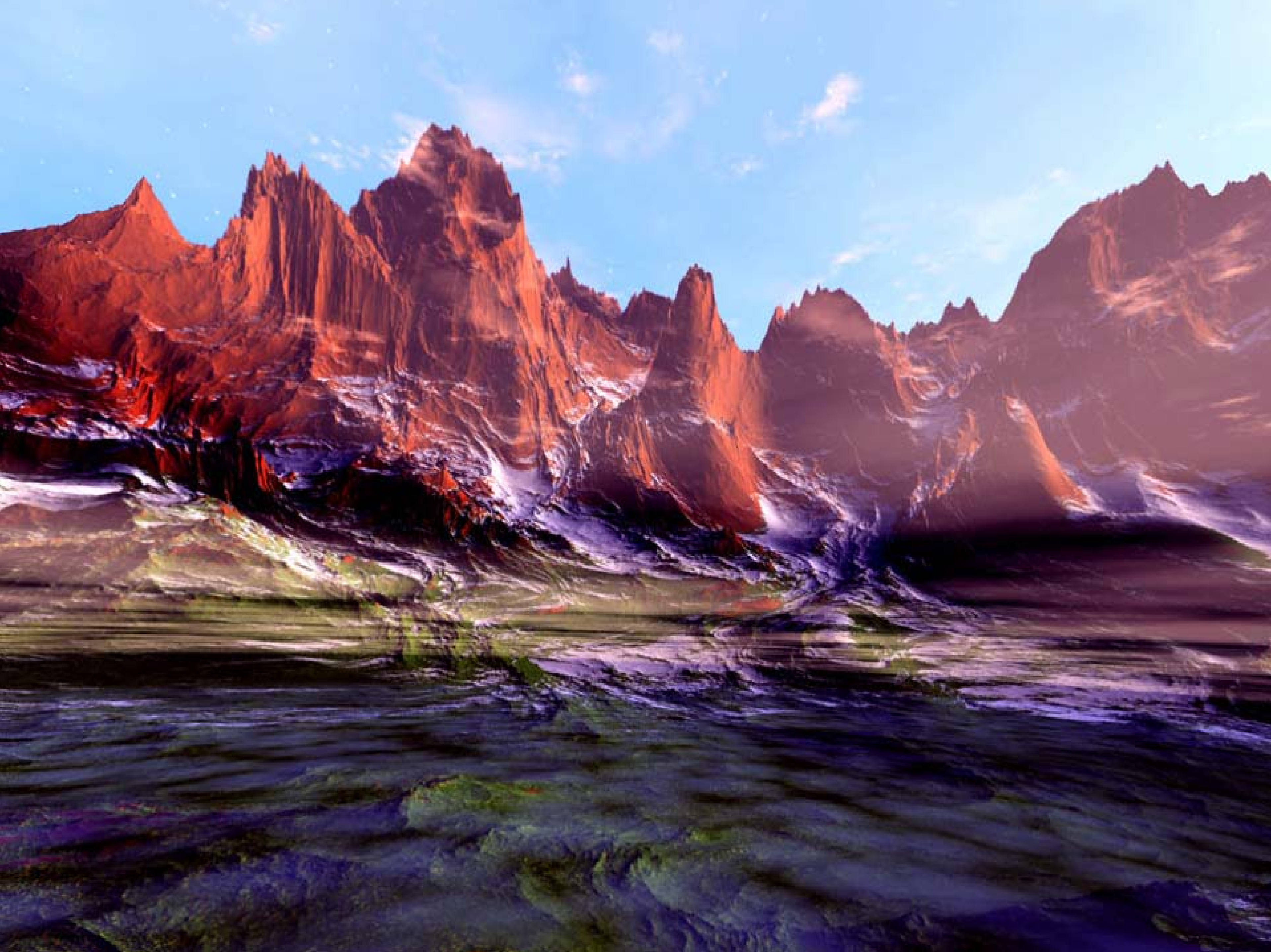
⇒LUT size reduced by a factor of 29!



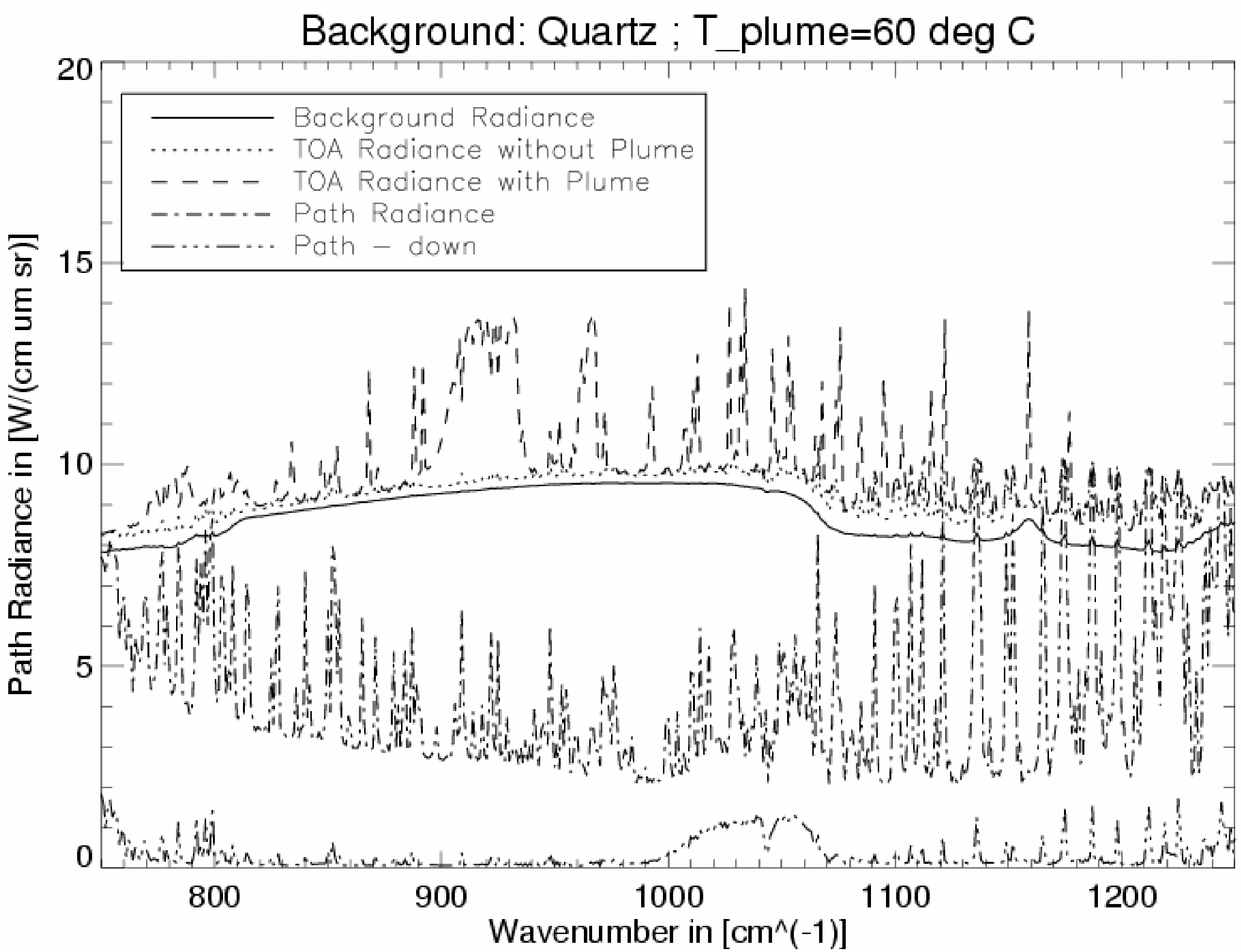


Conclusions

- **The new combination of smooth emissivity retrieval and in-scene atmospheric correction is able to retrieve temperature and emissivity for many atmospheres**
- **Temperature error is 0.16 K for new combined method (0.81 K for ISAC) – factor of 5 improvement**
- **RMS emissivity error is less than 0.005 for new method versus 0.02 for ISAC – factor of 4 improvement**
- **New temperature search method improves speed by at least 10 x over linear and 50 x over gradient-search**
- **Next step: Validate the ISAC & smooth emissivity retrieval algorithm on real data**

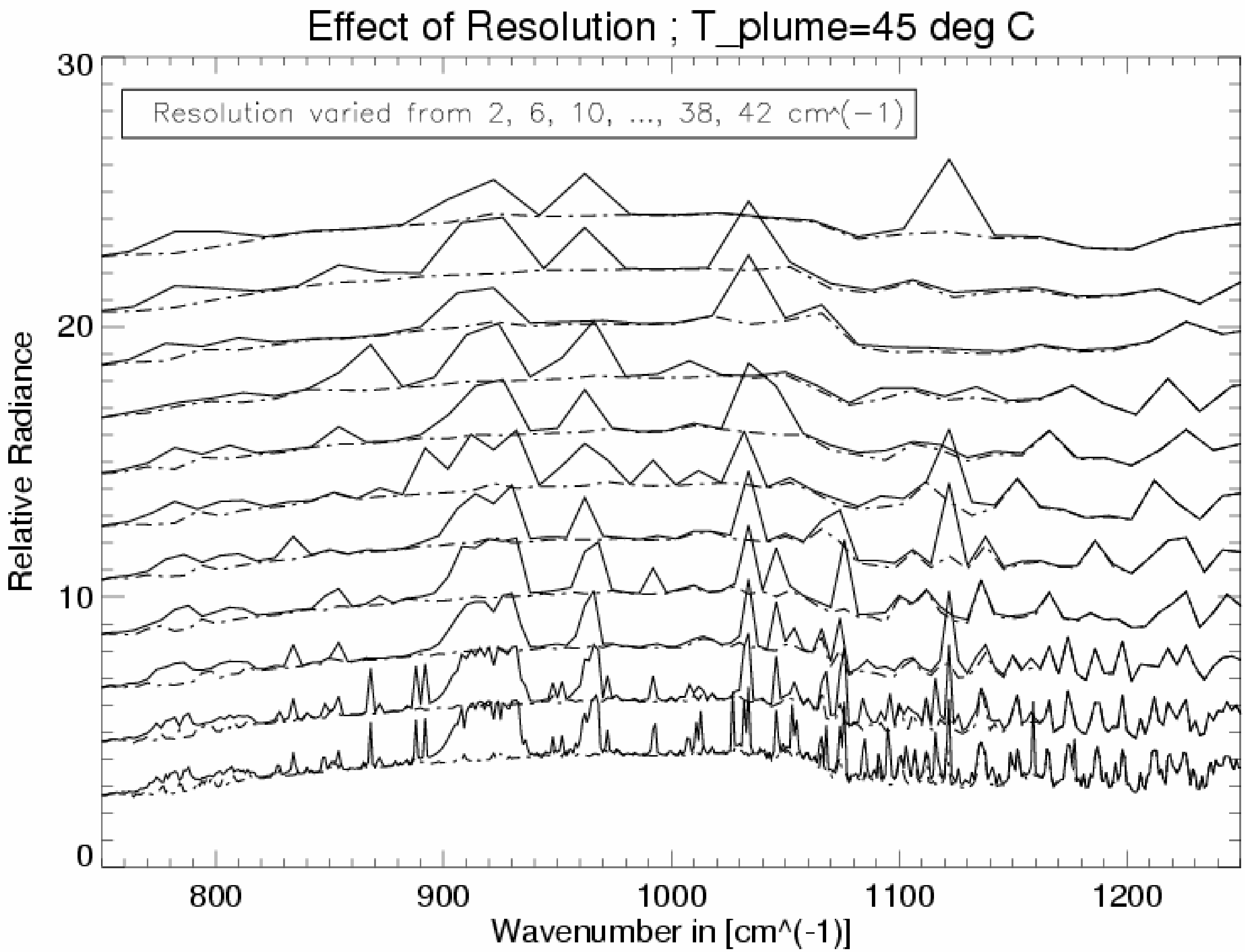


Example of scene spectrum



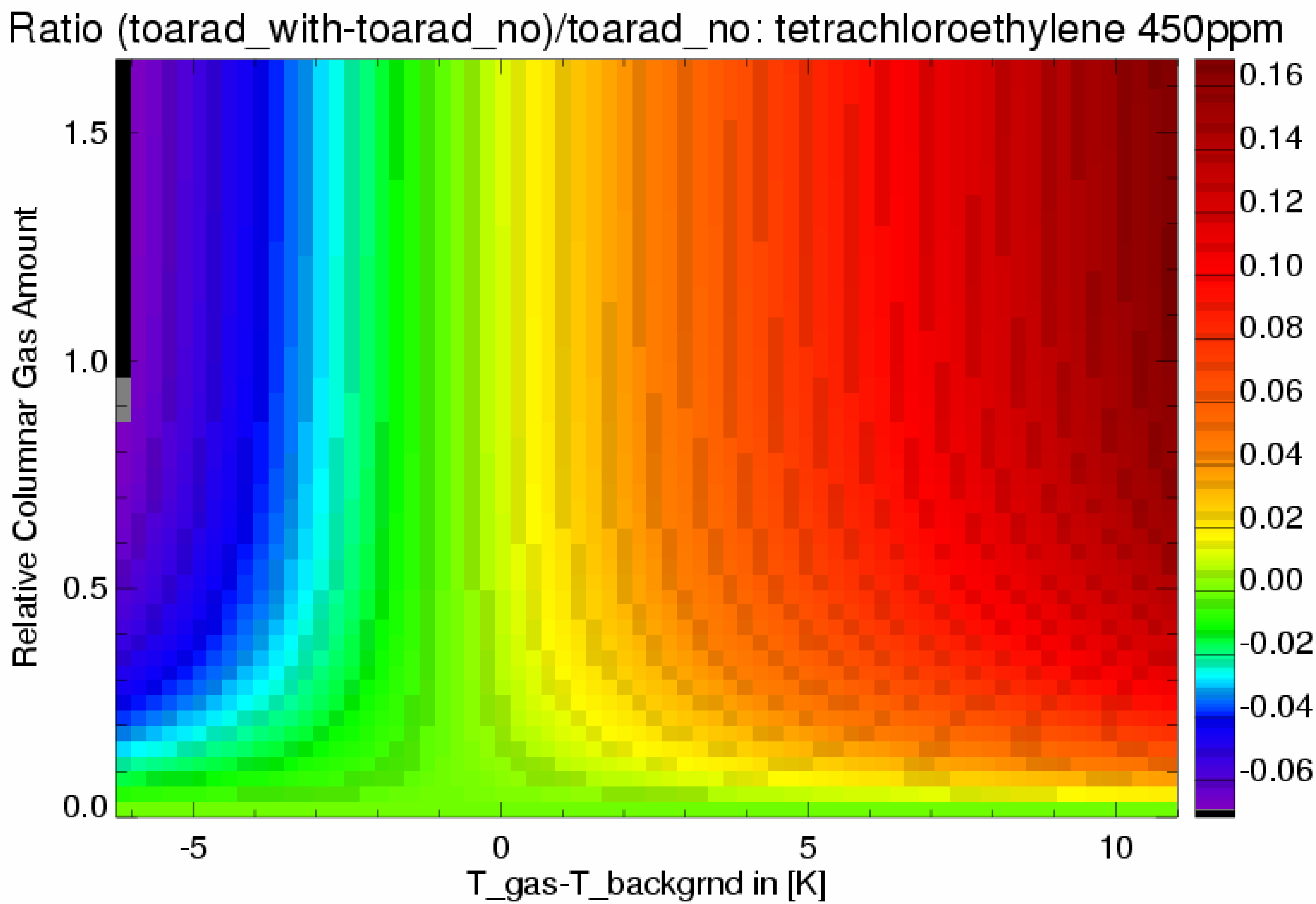
Mixture of 60 deg C gases (500 ppm Ammonia and 450 ppm tetrachloroethylene) radiances computed over quartz surface at 32 deg C.

Effect of resolution on spectra



The effect of spectral resolution on the on-plume (solid line) and off-plume (dashed line) radiance.

Plume temperature contrast



$(On - Plume - Off - plume)/(Off - Plume)$ ratio for TCE

Assumptions for smooth emissivity TES

- Perfect sensor (no spectral and radiometric errors),
- Spectral range in the TIR from 7.5 to 13.9 μm with 100 or more spectral channels
- The atmosphere is assumed to have the transmission and path radiances of a US standard atmosphere with a thin cirrus cover.
- The flight altitude was set to 3.7 km with a surface at 1.31 km above sea level.
- No mixed pixels - one material and temperature per pixel.